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FY 1989 ANNUAL REPORT

EXPLORATION STUDIES TECHNICAL REPORT
Volume 0: Journey into Tomorrow

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This publication is one of seven documents describing work performed in fiscal year 1989 under the auspices of the Office of Exploration. Volume 0, titled "Journey Into Tomorrow," provides an overall programmatic view of the goals, opportunities, and challenges of achieving a national goal for human exploration. The technical details and analyses are described in the other six volumes of the series. Volume I is Mission and Integrated Systems; Volume II is Space Transportation Systems; Volume III is Planetary Surface Systems; Volume IV is Nodes and Space Station Freedom Accommodations; Volume V is Technology Assessment; and Volume VI is Special Reports, Studies, and In-Depth Systems Assessment. These seven volumes document the status of Exploration Technical Studies at the conclusion of the FY 1989 study process in August 1989, and, therefore, do not contain any analyses, data, or results from the NASA 90-Day Study on Human Exploration of the Moon and Mars.

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16. Abstract

The Office of Exploration (OEXP) at NASA Headquarters has been tasked with defining and recommending alternatives for an early 1990's national decision on a focused program of human exploration of the solar system. The Mission Analysis and System Engineering (MASE) group, which is managed by the Exploration Studies Office at the Lyndon B. Johnson Space Center, is responsible for coordinating the technical studies necessary for accomplishing such a task. This technical report, produced by the MASE, describes the process that has been developed in a "case study" approach. The three case studies that were developed in FY 1989 include:

1. Lunar Evolution Case Study, 2. Mars Evolution Case Study, 3. Mars Expedition Case Study. The final outcome of this effort is a set of programmatic and technical conclusions and recommendations for the following year's work.

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The Office of Exploration FY 1989 Annual Report

Exploration Studies Technical Report Volume 0: Journey into Tomorrow

NASA

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PREFACE

Prior to the President's July 20, 1989, speech announcing the Space Exploration Initiative, NASA's Office of Exploration was engaged in the second phase of a series of exploration studies. The first phase, which began in June 1987, encompassed four case studies, and culminated in the 1988 report titled, *"Beyond Earth's Boundaries,"* and its three-volume companion series, Technical Memorandum 4075, titled, *"Exploration Studies Technical Report: FY 1988 Status."*

Subsequent to the 1988 report, the Office of Exploration initiated follow-on case studies, controlled trade studies, and special assessments. In mid-1989, however, NASA redirected its efforts to study specifics of the President's announcement on the Space Exploration Initiative. The seven volumes contained in this Technical Memorandum provide the results of those early 1989 technical studies. The *"Report of the 90-Day Study on Human Exploration of the Moon and Mars"* contains the results of study efforts after the President's speech.

Because the technical data and analysis generated during the 1989 studies continue to be of value to the development of plans for implementing the President's goals, this series of technical publications will make the data available as a reference for ongoing and future work.

INTRODUCTION

Since June 1987, the NASA Headquarters Office of Exploration has been leading a NASA-wide effort to provide recommendations and alternatives for a National decision on a focused program of human exploration of the solar system. The results of these studies are documented annually in the Exploration Studies Technical Report.

The Office of Exploration's FY 1989 Annual Report is a publication in seven volumes, of which this is the first. This volume provides a technical and programmatic overview of the year's effort. Volume I, Mission and Integrated Systems, contains the results of the total synthesis and analysis of technical studies performed during FY 1989. Much more detailed descriptions of assessments and trade studies performed in the specific areas of Space Transportation Systems, Planetary Surface Systems, Nodes and Space Station Freedom Accommodations, and Technology Assessments are provided in Volumes II, III, IV, and V respectively. Volume VI is a collection of special reports, studies, and in-depth systems assessments.

The objective of these exploration studies has been to determine how to meet the National Space Policy goal to "expand human presence and activity beyond Earth orbit into the solar system." Although the goal itself is clearly stated, many possibilities exist for the way in which human presence in the solar system could be achieved and sustained. To organize and systematically examine a broad spectrum of options, a study methodology was formulated that embraces the technical and programmatic elements of pursuing this goal.

First, the Office of Exploration defined potential "pathways" into the solar system that describe the exploration destination(s). Pathways may lead to a single destination, such as the Moon, Mars, an asteroid, or one of the Martian moons Phobos and Deimos. Other pathways link destinations, such as a pathway to the Moon and then Mars (the pathway President Bush selected), to Phobos and then Mars, to Mars and then the Moon, and so on. Defining these pathways was a useful starting point, but other major questions, such as "why explore," "how to explore," and "what to explore" needed to be addressed in parallel.

A variety of reasons might drive human exploration. Intellectual or political aspiration could be the motivation, or the desire for commercial gain, scientific advancement, or technological achievement could prevail. Domestic or international considerations could dictate the strategy. To examine this issue, NASA reviewed seven major themes and rationales for exploration: national pride and international prestige, advancement of scientific knowledge, technology catalyst, economic benefits, space enterprise, international cooperation, and education and excellence.

To begin to study the immediate question of how the Nation might venture forth into the solar system, the Office defined three strategies (evolution, expedition, and science outpost) that respond to different rationales for exploration. The strategy that is chosen is largely a function of the reason for going. These alternative strategies, combined with specific exploration pathways, formed a useful basis for addressing the second set of technical and operational questions: "how and what."

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Volume VI:	*Special Reports, Studies, and In-Depth Systems Assessments*

In the **Evolution Strategy**, permanent human presence would be established on another planetary body, with the goal of becoming largely independent of Earth. A step-by-step, long-term program would begin with a small human-tended facility and evolve into a complex, nearly self-supporting outpost with reusable transportation vehicles and permanent habitation, scientific, and laboratory facilities.

In contrast, the **Expedition Strategy** emphasizes one or a few missions, with a visible, accelerated effort to establish the first human presence on another planetary body. Current technologies and capabilities would be used to mount an Apollo-style program in which the goals are to safely reach the objective, conduct exploration activities for a short time, install long-term monitoring devices, and return to Earth. The vehicles and habitats are usually expended at the end of each mission.

Last, the **Science Outpost Strategy** focuses on establishing an extraterrestrial human-tended scientific facility used to advance knowledge in areas such as astronomy, geology, exobiology, and atmospheric and planetary science. Building the facilities, and remaining on the Moon long enough to do so, offers the opportunity to gain operational experience living and working on an extraterrestrial body. Scientific research would be performed using the Moon as a platform for long-term observatories, and the outpost would also serve as a staging base for establishing a human outpost on another planetary body.

The Office of Exploration, in concert with the other NASA program offices, examined in detail a number of potential approaches to implementing these strategies. In-depth studies conducted over the past 2 years provided NASA with a solid preliminary understanding of the overall requirements for realizing any exploration program. The approach inherent in this effort was to build on past studies, focus on feasible approaches, and develop a substantial base of knowledge on technical and programmatic requirements as input to the President for defining a pathway for the human exploration of the Moon and Mars.

NASA study efforts examined the following areas of major systems trades that provide insight into the needs for human space exploration:

- Launch vehicle size versus on-orbit assembly
- Alternative propulsion systems, including chemical, nuclear, and aerobrakes
- Extent to which life support systems should be closed
- Artificial gravity versus microgravity countermeasures
- Alternative approaches to and location of transportation nodes, including *Space Station Freedom* evolution
- Communication requirements and alternatives
- Alternative approaches to habitats
- Reusable versus expendable vehicles
- In situ resource utilization versus Earth-based logistics
- Photovoltaic versus nuclear surface power systems
- Rigid and inflatable habitats
- Man-tended versus permanently manned facilities.

These studies demonstrated that, regardless of the specific pathway selected, human exploration missions consist of several fundamental elements, each of which can be implemented in a variety of alternative ways. First, cargo and crew must be lifted from Earth to low Earth orbit. The way in which this could be accomplished can range from multiple launches of a small vehicle to a single launch of an extremely large vehicle. Then, once hardware and personnel have arrived in low Earth orbit, the vehicles that transfer the crew and cargo from low Earth orbit to lunar or Mars orbit must be prepared for the next phase of the journey, an operation that could vary widely in degree of complexity. If a node is required, *Space Station Freedom* could support this operation, or a separate facility could be built solely for this purpose. The transfer vehicles themselves could be reusable, and stored in low Earth orbit for this mission phase, or they could be expendable, launched from Earth for a single use. Several alternative propulsion systems could be used to power these vehicles. Similar alternatives exist for the excursion vehicles that provide transportation from planetary orbits to planetary surfaces.

On the surface of the planet, the range of required systems can vary widely, depending on the planned level of activity and length of stay time. For short visits, the crew can live in the excursion vehicle. For longer periods, pre-built habitation and laboratory modules, such as those derived from *Space Station Freedom* systems, may suffice. For long-term habitation, constructible habitats and laboratories may be used. Similarly, the level of capability of power systems and life support systems would be a function of the level of activity on the planetary surface.

This document summarizes study results and lessons learned in working to understand these types of alternative approaches to conducting human exploration of the solar system. The pages that follow provide a programmatic view of the studies conducted by NASA prior to the President's July 1989 speech. These exploration studies formed, in part, the technical basis for the President's decision, announced on the twentieth anniversary of the Apollo 11 landing on the Moon. The last section of this volume provides a general overview of events leading to that decision. In the sections immediately following, human exploration case studies, and the related NASA programs that would be required to support them, are described. The scientific aspect of human exploration is also addressed, followed by a summary of conclusions and recommendations.

HUMAN EXPLORATION CASE STUDIES

The primary objective of the Office of Exploration during the first half of 1989 was to analyze combinations of human exploration pathways and strategies to outline the parameters of various mission options. These combinations were tested with "case studies," which were intended not simply to describe specific realistic mission scenarios, but rather to provide the technical framework within which various approaches to human exploration of the solar system could be examined, analyzed, and compared. Although an approach was adopted to examine a broad spectrum of alternatives, past experience defined the fundamental structure for such missions. Case studies do not represent recommended approaches, but are merely tools to understand various technical and programmatic options.

To develop case studies that might prove feasible, the definition process began with the selection of high-level ground rules, including mass-to-orbit limitations, launch date restrictions, limits on number of crew, vehicle assembly strategies, and estimates of mission duration. Within these ground rules, an end-to-end analysis was performed of the key elements that compose a human exploration case study: mission definition and architecture, science opportunities and strategies, transportation systems, orbital nodes, and planetary surface systems. The results of this analytical process helped to build an understanding of the feasibility and benefits of the various approaches, enabling the identification of the most appropriate implementation of various case study elements.

In parallel with the case studies, special assessments, controlled trades, and studies to encourage additional innovative ideas were used to examine related technical areas that were not linked to any specific case study, but rather could provide significant insight into the overall issues associated with human exploration. These studies covered such areas as in situ resource development and use, unique or exotic propulsion systems, power production, and other subjects.

The material presented below outlines the seven case studies analyzed during the past 2 years. The four 1988 case studies are mentioned briefly so that the reader is aware of what has been done in the past; the results are more thoroughly documented in *Beyond Earth's Boundaries*, the Office of Exploration's 1988 Report to the Administrator. Then, for each of the three 1989 studies, the major ground rules, the most significant findings, and programmatic assessments are discussed. The 1989 case studies are described in greater technical detail in Volume I of this document set.

1988 Case Studies

Four case studies were evaluated during 1988: Human Expedition to Phobos, Human Expeditions to Mars, Lunar Observatory, and Lunar Outpost to Early Mars Evolution. The two expedition studies focused on achieving human exploration of the solar system as early as possible, in one case by sending humans to the surface of Mars, in the other to the Martian moon Phobos. The Lunar Observatory case study was analyzed to evaluate the feasibility and scientific benefit of establishing an astronomical facility on the lunar surface. The fourth 1988 case study, Lunar Outpost to Early Mars Evolution, examined an evolutionary strategy wherein human explorers establish a permanent lunar outpost that is subsequently used as a staging base for journeying to Mars.

1988 CASE STUDIES

1. *Human Expedition to Phobos*
2. *Human Expeditions to Mars*
3. *Lunar Observatory*
4. *Lunar Outpost to Early Mars Evolution*

The Human Expedition to Phobos case study offered the capability of achieving a landing on the surface of another world more than 4 years earlier than a mission to Mars, and Phobos also showed promise as a location for an in situ propellant plant to produce fuel for further exploration. The case study also yielded results indicating that Earth launch requirements can be brought within a practical range for Shuttle-derived launch vehicles by using aerobraking, using an integrated Earth launch vehicle/Mars transfer vehicle, and reducing the number of crew members.

The Human Expeditions to Mars, a three-mission series, proved to be very transportation-intensive, particularly if the launch date is constrained; performance and requirements for trajectories to Mars can vary widely with launch year and corresponding celestial geometry. Because of the large number of Earth launches, the high level of in-space assembly and fueling operations and the resulting cost, and the required short stay times at Mars, this case was not considered practical within the 1988 development ground rules.

The human-tended Lunar Observatory case indicated that a significant scientific outpost on the Moon could be established and operated with a comparatively modest and constant mass to low Earth orbit. A scientific observatory on the Moon also appeared to be a productive step as part of an evolutionary strategy to develop an outpost on the Moon.

The Lunar Outpost to Early Mars Evolution case study demonstrated the potential benefits of using extraterrestrial resources in a long-term, sustained program. The concept of using the Moon as a learning base for further human exploration of the solar system also showed significant promise.

These key results and findings of the 1988 case studies formed the basis for the definition of the three 1989 case studies, described below.

1989 Case Studies

Three case studies were chosen for 1989: Lunar Evolution, Mars Evolution, and Mars Expedition. These case studies were selected to build on and refine the information gained during 1988, and a clear correlation can be seen between the 1988 and 1989 case studies. The Lunar Evolution, for example, examined in more detail the lunar portion of the Lunar Outpost to Early Mars Evolution, and elements of the Lunar Observatory case study were also incorporated into the case study definition. Similarly, the Mars Evolution case study more comprehensively examined the Mars portion of the 1988 evolutionary case, with some elements of the 1988 Human Expeditions to Mars and Phobos.

1989 CASE STUDIES

1. *Lunar Evolution*
2. *Mars Evolution*
3. *Mars Expedition*

Finally, the 1989 Mars Expedition provided a direct comparison between one-mission expeditions to Mars and Phobos, and also sought to define a more practical expeditionary route to Mars.

The analysis of mission element relationships was enhanced by special assessments and controlled trade studies that examined alternative approaches to techniques defined as case study ground rules. Special assessments in 1989, for example, focused on issues that are potentially beneficial to all mission options: power systems, propulsion systems, life support, and automation and robotics. In cases where results of these studies isolated techniques that showed particular promise, the technique involved was applied to the continuing case study development.

Similarly, controlled trade studies were conducted to examine particular areas in which results are essential to further develop the case studies or to address key case study constraints. Three 1989 trade studies — Earth-Moon node location, lunar liquid oxygen leverage, and launch/on-orbit operations — further matured technical understanding in these areas. Significant results of these trade studies and special assessments are discussed in the sections describing case study findings. More detail is provided in Volume I of this series.

LUNAR EVOLUTION CASE STUDY

Description

The objective of the Lunar Evolution case study was to examine one approach to establishing a permanent human lunar outpost, which would support significant science objectives yet serve as a test-bed and stepping-stone for further human exploration of the solar system. The outpost would gradually evolve to a high degree of self-sufficiency to allow future exploration initiatives to be undertaken within a steady level of national investment. As defined by the ground rules of this case study, *Space Station Freedom* would be used as the staging location between Earth and the Moon. Transportation vehicles would be expended after each mission for the first 2 years to increase payload capability to the lunar surface; after that, the vehicles would be reused, with transfer vehicles serviced at *Space Station Freedom* and excursion vehicles serviced on the lunar surface. Aerobraking, a technique whereby a planetary atmosphere is used to decelerate a spacecraft, would be employed on return to Earth. The number of crew members would begin at four, increasing to 12 as the outpost developed.

The Lunar Evolution case study sought to better understand the physiological needs and responses of human explorers living in low-gravity, constrained environments, and to define protective living and efficient work support systems. The case also addressed the potential for both in situ lunar exploration and the development of a lunar-unique remote sensing capability. It further examined the possibility of using lunar materials to develop resources that could be used to support the growth and operation of the outpost. Above all, these objectives were pursued in an evolutionary and flexible manner. Reflecting this progressive character, the development of a lunar outpost was divided into three phases — emplacement, consolidation, and utilization — each of which represents a progressively higher level of commitment, understanding, and capability.

LUNAR EVOLUTION CASE STUDY GROUND RULES

- ***Space Station Freedom*** *would be used as the staging location between Earth and the Moon.*
- ***Transportation vehicles*** *would be expended after each mission for the first 2 years.*
- ***Aerobraking*** *would be employed on return to Earth.*
- ***The number of crew members*** *would initially be four, later increasing to 12.*

Emplacement Phase. This first phase would establish permanent human presence on the Moon and begin developing operational experience on how to live and work on a nonterrestrial body. Initial instruments and equipment would be installed on the lunar surface, and the foundation would be laid for later, more complex surface operations. The first crew of four would stay on the lunar surface for up to 30 days, and they would set up and check out the initial support and habitation systems delivered on an earlier cargo mission. The initial habitat would be a "pre-built module" derived from *Space Station Freedom* habitation modules, modified for the one-sixth lunar gravity and powered by solar photovoltaic arrays with regenerative fuel cells for the long (14 Earth days) lunar nights. A 6-month period of unmanned testing and verification of these facilities would follow. Concurrently, the transportation infrastructure would be emplaced, including lunar transfer vehicles, which transport cargo and personnel between low Earth orbit and lunar orbit, and lunar excursion vehicles, which shuttle payloads and crew between lunar orbit and the lunar surface.

Permanent habitation would begin with the arrival of a second crew of four, who would stay at the outpost for 6 months. This crew would build basic facilities, conduct critical life sciences investigations of human adaptation to the lunar environment, and test methods for extracting oxygen from lunar soil. Human activity and exploration would take place within tens of kilometers of the outpost, complemented by a local unpressurized rover. Science activities at the outpost would nonetheless be vigorous and would include geophysics and laboratory geochemistry, as well as solar remote sensing, optical astronomy, and radio interferometry. Hundreds of kilograms of lunar soil samples would be collected and returned to Earth for analysis. An initial launch/landing facility at the outpost would support one lunar excursion vehicle.

The emplacement phase would conclude with the arrival of four crew members, who would inhabit and work at the outpost for 12 months. To accommodate the increased stay time and activity, the photovoltaic power system would be enhanced to provide 200 kilowatts during the day and 50 kilowatts at night. Both the transfer and excursion vehicles would be reused at this point; the transfer vehicle would be serviced at *Space Station Freedom*, and the excursion vehicles would be serviced at the outpost. The launch/landing facility would be enhanced to support two lunar excursion vehicles, and scientific exploration would expand through the use of an instrumented teleoperated rover.

Consolidation Phase. The objective of this phase would be to sustain permanent human presence on the Moon and substantially expand operational experience in living and working on the surface of a low-gravity extraterrestrial body. The habitat would be expanded by adding an inflatable constructible module to the original facility; with this addition, permanent habitation facilities would be provided for up to 12 crew members. The launch/landing facility would support three lunar excursion vehicles, and both transfer and excursion vehicles would be reusable for up to 10 missions. Outpost power would be increased through the use of a small nuclear power plant, with total outpost power levels reaching 300 kilowatts during the lunar day and 150 kilowatts during the lunar night. Communications systems would also be enhanced.

The crew would increase to eight people with continuous stays up to 2 years. To accommodate the increased activity level, emphasis would be placed on constructing (rather than emplacing) surface systems, providing large pressurized volumes for significant laboratory science, and setting up more complex scientific instruments and laboratories.

Human exploration would expand to within hundreds of kilometers of the outpost with an enhanced pressurized rover, and outpost astronomy would benefit from the addition of more telescopes in both higher and lower-energy bandwidths. Self-reliance would increase with the addition of more efficient life-support systems and with the experience of performing day-to-day activities without continual supervision and guidance from support staff on Earth. As confidence and capability in outpost operations improved, the supply line from Earth would diminish.

Late in the phase, full-time operational capacity would occur with the installation of an 825-kilowatt nuclear power plant. Prototype testing of an in situ resource production plant for such materials as lunar liquid oxygen would be conducted in preparation for full-scale production during the next phase.

Utilization Phase. In this final phase of lunar outpost development, lunar resources would be used to enhance self-sufficiency. Operational experience in living and working in an extraterrestrial environment, largely independent of Earth, would continue to mature. Earth logistics and operational support would be substantially reduced to make resources available for other human planetary exploration. The number of crew would increase to 12, with tours of 2 years. The range of human exploration would increase significantly, becoming global through the addition of ballistic excursion vehicles, and extending to man-tended facilities on the lunar farside and access to other points on the lunar surface. Science capabilities would include plant/animal/microbe experiments, continued geological and geophysical exploration, and enhanced observational facilities, including a lunar farside low-frequency radio array and geophysical stations. Full-time lunar oxygen production would begin, and the oxygen would be used for life support and as fuel for the excursion vehicles based at the outpost. An additional year of growing capability would occur before steady-state lunar outpost operations were achieved. Thereafter, the knowledge base gained from developing a self-sufficient, established lunar outpost would foster future human exploration opportunities.

Findings

The findings that emerged from this case have both near-term and strategic planning implications. Most significant, the introduction of lunar oxygen production in the utilization phase had a substantial impact on Earth logistics and support mass requirements, cutting launch requirements in half. This capability, combined with maturing confidence in the outpost infrastructure and operations and the ability to use the Moon as a base for life sciences research, opens a significant opportunity to expand human presence to other planets, most notably Mars. The maximum benefit of using lunar oxygen is realized when it is used to fuel lunar excursion vehicles. For other transportation applications, the benefit decreases proportionally as distance from the lunar surface increases. Nonetheless, using lunar oxygen to fuel the excursion vehicles provided a substantial savings in Earth-to-orbit payload requirements.

The in-space propulsion system selected for the case study was chemical with aerobraking at Earth. Several alternative efficient low-thrust systems were also investigated; however, because of the relatively large differences in the masses of Earth and the Moon, these systems require a very long time to spiral out from low Earth orbit, and they spend an excessive amount of time in Earth's radiation belts, which poses a hazard to the crew and damages the spacecraft electronics. Because of the short travel time between Earth and the Moon, nuclear thermal rockets did not appear to offer any major advantage as an alternative propulsion in the context of this case, but future studies will investigate the capability of this technology to reduce payload mass for lunar missions.

Another important finding was in the area of transportation requirements for an evolutionary lunar outpost. For transportation from Earth to *Space Station Freedom*, initial case study ground rules stipulated the use of a launch vehicle that can lift at least 140 metric tons. However, as the case study analysis matured, it was determined that the entire case could be accomplished using the Space Shuttle and Shuttle-derived heavy lift launch vehicles or similarly capable Advanced Launch System vehicles. A maximum of six cargo launches per year of 71 metric tons of payload each is required during the first decade of outpost development, after which the rate falls to three per year. Transportation of four crew members per flight twice a year by the Space Shuttle during the first decade would decrease to one launch per year thereafter.

For in-space transportation, the lunar transfer vehicle and lunar excursion vehicle can be designed to be reusable, which offers attractive savings in the number of vehicles needed. In addition, both the transfer and excursion vehicles were designed to be used for either a pure cargo mission or a combined personnel and cargo mission by simply adding a crew module for personnel missions. The use of a single vehicle design appears to reduce cost and simplify flight operations and servicing.

With several key upgrades, *Space Station Freedom* was determined to provide appropriate capability as a transportation facility. The upgrades include additional solar dynamic power, vertical booms, servicing bay, and enhanced crew support and logistics capabilities. These enhancements to *Freedom* would enable assembly of the payload stacks for lunar transport, and servicing and storage of the reusable lunar transfer vehicles.

Assessment

Expanding human presence and activity beyond Earth orbit requires the ability to sustain people at selected solar system sites for long periods of time under acceptable and effective living and working conditions. Yet such a challenge demands technical capabilities and experience beyond those found in the space program today. From this perspective, the Moon is an ideal location for creating an initial space outpost on which to develop essential life-support capabilities, validate critical systems and operational concepts, and pursue significant scientific exploration objectives.

The Lunar Evolution case study represents a straightforward phased approach to lunar outpost development. The rationale for constructing a lunar outpost includes the ability to conduct astronomical, geological, and other scientific research, as well as to investigate life sciences and other issues associated with sending humans safely to Mars and beyond. A lunar outpost similar to the one described in this case study could be developed in the early years of the next century. With a number of near-term investments identified, such as completion and evolution of *Space Station Freedom*, development of a heavy lift launch vehicle, and advances in a few important technologies (aerobraking, in situ resource utilization, etc.), this case study demonstrated how humans could establish a permanent presence on the Moon.

MARS EVOLUTION CASE STUDY

Description

The objective of the Mars Evolution case study was to examine one approach to develop a permanent, largely self-sufficient Mars outpost with significant scientific research capability. A second objective was to explore the possibility of developing a "gateway" on the Martian moon, Phobos, for the production of propellant. Ground rules for this case study stipulated that space transfer vehicles would be assembled at a free-flying man-tended assembly fixture co-orbiting with *Space Station Freedom* in low Earth orbit, and aerobraking techniques would be used at both Mars and Earth. Artificial gravity would be provided in the spacecraft that transport the crew to and from Mars.

The Mars Evolution case study was divided into the same three phases as the lunar case: emplacement, consolidation, and utilization, with each phase representing a progressively higher level of commitment, understanding, and capability.

Emplacement Phase. This phase would establish the initial human presence on Mars. First, a cargo vehicle carrying the initial surface habitat, construction equipment, a rover, a photovoltaic power supply, and communications equipment would be deployed to Mars. The cargo vehicle would remain in orbit, and only the unmanned semiautonomous rover would be deployed to the prime landing site region. For several months, the rover would explore the region and identify the precise landing site for the cargo remaining in orbit during this reconnaissance period. After the cargo has landed, a crew of four would descend in the Mars excursion vehicle to the surface of Mars for 30 days. Although this first crew would live in the excursion vehicle, one objective of their short stay would be to verify the integrity of the initial surface habitat for use by later crews. Local human exploration and scientific investigation would be conducted using a pressurized rover to range tens of kilometers from the outpost, and an unmanned rover would explore within hundreds of kilometers of the outpost. A scientific payload would be robotically deployed to Phobos to reconnoiter its resources and to return a sample of Phobos to the piloted spacecraft for subsequent analysis to verify the use of Phobos as a propellant gateway. A robotic orbiter would be deployed to the other Martian moon, Deimos, for scientific exploration.

The next piloted flight would bring a crew of five, who would remain on Mars for approximately 16 months, living in the habitat emplaced by the first crew. This crew's primary objectives would be to demonstrate the feasibility of long-term habitation of Mars and to conduct intensive regional scientific and exploratory investigations in the vicinity of the outpost. A pressurized rover would be provided for human exploration of scientifically interesting areas. Later in the phase, a propellant (hydrogen and oxygen) plant would be robotically delivered to Phobos. Launch and landing facilities would also be established on Mars.

Significant scientific research would be performed by the second crew during the emplacement phase. Working in much the same way as geologists on Earth, they would study Martian rocks, sediments, stratigraphy, and local geomorphology, search for signs of past or present life, determine subsurface shallow and deep structure of the planet, and observe atmospheric chemistry using balloons and rockets. Samples collected from different locations on the planet would be returned to the outpost for preliminary analysis, and then sent to Earth for further analysis. The area around the outpost would be explored to locate and evaluate local resources, such as minerals and, possibly, water. A small network of science stations would be deployed, both manually and robotically.

MARS EVOLUTION CASE STUDY GROUND RULES

- ***Space transfer vehicles*** *would be assembled at a free-flying fixture.*
- ***Aerobraking*** *would be used at both Mars and Earth.*
- ***Number of crew*** *would be four, later increasing to seven.*
- ***Artificial gravity*** *would be provided in the spacecraft that transport the crew to and from Mars.*

Consolidation Phase. The objectives of this phase would be to continue permanent human presence on Mars and to increase self-sufficiency from Earth. Two piloted flights would occur during consolidation. The primary tasks of the first crew of five would be to emplace and verify the Phobos propellant production plant and to conduct global exploration of Phobos to evaluate its geology and geophysics before descending to Mars for the remainder of their 18-month stay. The Phobos propellant production plant would be brought to full operational status during this time. The propellant produced would be used on the next flight. The second flight, also with a crew of five, would be a 16-month mission with the primary objective of expanding exploration and science activities on Mars.

Science objectives would include farther human and rover traverses to study the planet's geology and geophysics. Plant growth experiments and human adaptation research would be initiated. Analytical laboratory facilities would be upgraded to enable experimentation with resource utilization and materials processing. The science stations would grow in number and capability to increase understanding of Martian weather, dust storms, and geophysical properties. Unmanned rover exploration capability on Mars would expand to thousands of kilometers.

Utilization Phase. The objectives of the third phase would be to use local Martian resources to produce oxygen and to continue to develop operational experience living and working independently in an extraterrestrial environment. The phase would advance with the cargo delivery of an in situ resource utilization plant and a constructible habitat capable of housing 12 people, followed by the landing of a crew of seven, who stay for 21 months.

Use of the Mars outpost to perform science would continue, with emphasis on the search for indigenous life and on an expanded life sciences effort in support of plant growth experiments, experiments with microbes and animals, and additional studies of human adaptation.

Findings

The Martian moon Phobos was analyzed as a possible source of hydrogen and oxygen fuel for Mars transfer and excursion vehicles to determine whether this technique could greatly reduce the amount of fuel delivered to Mars from Earth. Phobos is in a circular orbit around Mars, whereas incoming Earth/Mars transfer vehicles would be in a highly elliptical orbit about Mars to reduce fuel requirements. The transfer vehicles would need to expend a great deal of energy (and therefore propellant) just to reach Phobos. Within the ground rules and constraints of this particular case study, the requirement for additional propellant to perform this maneuver outweighs the savings achieved by producing propellants at Phobos. However, as was the case with the Lunar Evolution case study, the use of local resources shows more benefit nearer the outpost, and the benefit of Phobos propellants for use in the Mars excursion vehicle requires further study. Future studies should also focus on the potential for producing propellants from the Martian atmosphere or soil for use in spacecraft propulsion systems.

Shortening travel time to Mars may be important. At this time, the effect that spaceflight of a year or longer has on the health of the crew is not well understood. A number of Earth/Mars trajectories were identified that would reduce one-way travel time to Mars to approximately 5 months and would also enable the crew to perform a Mars swingby maneuver in an abort situation. This swingby would propel the craft back to Earth if a problem occurred with the rocket stage that is normally used to return the crew to Earth; however, in an abort situation, the total time spent in space would be about 3 years.

As specified by case study ground rules, the use of a rotating artificial gravity vehicle to transfer crew from low Earth orbit to Mars was analyzed using a hydrogen/oxygen propulsion system with an aerobrake to assist in the Mars and Earth entry portions of the trip. Both rigid and tethered artificial gravity vehicle designs have been evaluated in previous studies. For this 1989 case study, the vehicle considered has two cylindrical habitat modules that swivel out during flight while the vehicle rotates about its central axis, creating artificial gravity for the crew. This design does not have some of the complexities associated with a tethered vehicle; however, because of its limited diameter, it could not produce the same low spin-rate, high gravity-level environment as a tethered vehicle. Therefore, if life sciences research indicates that artificial gravity is required for Mars missions, further analysis will be necessary to quantify the spinrate and gravity level required to maintain the health of the crew on long-duration flights. This research must be completed before the optimum spacecraft configuration can be determined.

Several alternative propulsion systems were examined for potential improvement over the chemical/ aerobraking system stipulated as the case study ground rule. Of these systems, nuclear rockets, which appear to significantly reduce launch requirements and/or decrease trip times, were determined to be a particularly attractive option for further research.

The use of the unique momentum exchange features of long tethers anchored at Phobos was a propulsion technique included in the original case study ground rules. As configured, tethers were used for both Mars landers and the piloted vehicles to provide momentum transfer from Phobos to Mars and for return to Earth. For this particular case study, the operational complexity and added mass of the tether system negated any savings. However, this technique may offer promise if the tethers are located in Mars orbit.

This case study also examined the feasibility of assembling the Earth to Mars transfer vehicle at a free-flying transportation facility co-orbiting with *Space Station Freedom* in low Earth orbit. Although this alternative offers some advantages, such as minimizing the impact on *Freedom's* facilities, it requires additional crew transportation and increases operational complexity. Further analysis is required, including ways to use *Freedom* to assemble, check out, fuel, and service Earth/Mars transfer vehicles. *Space Station Freedom* or a facility co-orbiting with it is also likely to be the location of a facility for life sciences research to provide the data required to make decisions regarding the gravity level and spin rate (if any) of a piloted Mars spacecraft.

Another important issue involved launching the Earth/Mars transfer vehicle, its crew, and propellants from Earth to low Earth orbit. A number of launch vehicles using Space Shuttle technology, as well as configurations of the planned Advanced Launch System, were analyzed that could lift the estimated 140 metric tons per launch required to support the Mars outpost. Further studies need to be performed to analyze how this heavy-lift capacity should be intermixed with Shuttle launches of assembly personnel and cargo.

Assessment

Mars is technically a more challenging target than the Moon, requiring much longer travel times, more robust engineering solutions, and more attention to complicated life sciences issues. The general goals for the exploration of Mars by humans encompass advances in various scientific disciplines, resource utilization, and self-sufficient, permanent habitation. A wide range of implementation possibilities and mission scenario options could be selected, but it is evident that a phased program of development and learning experiences can be key to a successful outcome.

The three-phase development strategy could effectively be applied to both lunar and Mars scenarios. However, unlike the Moon, where several robotic probes and 12 human explorers have already been, further research is required to resolve the many unknowns that remain concerning the Martian environment and methods of traveling to Mars. The physiological and psychological effects of long-term exposure to the zero gravity environment on the voyage to Mars and readaptation to the gravity level on its surface need to be determined. These factors must be understood before decisions can be made concerning Mars mission durations and the need for artificial gravity spacecraft. In addition, prior to sending human crews to the surface, robotic probes are required to thoroughly characterize the Martian environment, including the location of any hazardous substances and any valuable resources such as water.

A recurring theme throughout the Mars Evolution case study is the need for advances in technology and capability. New heavy lift launch vehicles, on-orbit assembly techniques and equipment, high-energy aerobraking, nuclear propulsion, and zero-gravity countermeasures are only a few of the areas in which significant development is required. Investment in technology development today is essential to meet the needs of an exploration mission to Mars during the next century.

Advances in life support system technologies beyond the currently planned system for *Space Station Freedom* are also vital to the development of a largely self-sufficient Mars outpost. Because of the large distances and long trip times associated with travel to Mars and the difficulties involved in repair and resupply of replacement parts, autonomous operation and reduced complexity and maintenance are critical in the design of advanced life support systems. Because an autonomous outpost life support system would use in situ materials to supplement or replace materials brought from Earth, additional information concerning the composition of the Martian atmosphere and soil is required before a determination can be made of which elements can be used to support the Mars outpost. For example, if future robotic probes discover water or other resources at specific locations on the Martian surface, the Martian outpost may be emplaced at one of these locations.

MARS EXPEDITION CASE STUDY

Description

The primary objective of the Mars Expedition case study was to determine how to accomplish a single human expedition to the surface of Mars as early in the 21st century as practical. In the course of the expedition, the environment, geological features, and material of Mars would be studied to advance knowledge of the origin of the solar system and to survey the potential for using Martian resources.

Two different trajectory options were initially considered for this case study. The first of these options was the "split/sprint" approach, carried over from the FY 1988 studies, in which a cargo vehicle delivers a portion of the cargo to Mars orbit, followed by a second vehicle carrying the crew and the remainder of the hardware. The second option was an "all-up" approach in which the crew and all the cargo are dispatched on one vehicle. Both options have similar characteristics regarding trajectory type and mission duration. The mission description below was based on the (new) second option.

Upon completion of the orbital mating operations between the vehicle and the propulsion stages, the three-member crew would depart for Mars in a zero-gravity transfer vehicle on a 500-day round-trip trajectory with a free flyby/return capability in case of mission abort. Depending upon the particular launch year, a Venus gravity-assist swingby might be utilized to reduce the trajectory energy requirements. Aerobraking, a technique that uses the planetary atmosphere to slow the vehicle, would be employed upon arrival to capture the spacecraft into a 500-kilometer circular orbit. Five days would be allowed for lander preparation, after which the excursion vehicle would separate from the cruise module, carrying all three crew members to the Martian surface.

MARS EXPEDITION CASE STUDY GROUND RULES

- *A single expendable vehicle would be launched to low Earth orbit.*
- *A zero-gravity vehicle would be used.*
- *Three crew members would descend to the surface for 20 days.*
- *Aerobraking would be used at Mars.*

During their 20-day stay on Mars, the crew would conduct geologic and geophysical observations near the landing site on foot and by rover, collecting rock, sediment, and exobiology samples. Instrumentation would be deployed for the crew to conduct short-duration experiments, such as seismic tests, atmospheric balloons and rockets, and microbe/bacterial/plant organics exposure tests. In addition, a geophysical/atmospheric science station would be left on Mars to measure properties and processes that can be monitored from Earth on a long-term basis. Because their stay on Mars is short, the crew would reside in the in-transit habitation module in the Mars excursion vehicle.

The crew would depart with selected surface samples to rendezvous with the interplanetary transport parked in orbit. Five days would be allowed for departure preparations, for a total stay time of 30 days at Mars. The return trajectory is either direct or by way of Venus, again depending on the launch year. As the interplanetary vehicle approaches Earth, the crew, with samples, would transfer to an Earth crew return vehicle and separate from the larger cruise module. Return to

Earth's surface would be via direct atmospheric entry and aeromaneuvering to landing. The total length of the mission would be 16 to 17 months.

Findings

In the time frame considered for this case study, there are four all-up mission opportunities to Mars. All outbound trajectories have a free-abort capability in the event of a major propulsion system failure detected en route to Mars as well as a powered abort capability in the event of some other system failure. Free aborts require longer-than-nominal trip durations (20 to 24 months); powered aborts can return the crew faster, but not in less than 13 months.

The major trade-off result showed that the all-up mission option is preferable to the split/sprint option on the basis of total mass required in low Earth orbit and the number of Earth-to-orbit launches. The split/sprint concept was modified from 1988's configuration by removing the trans-Earth injection stage from the cargo flight and placing it on the piloted flight to assure crew safety. This strategy then negated the mass advantage of a separate cargo flight.

Limited but important science can be accomplished on the Martian surface during the 20-day stay. Significant science investigations, referred to as "cruise science," could also be conducted on the long trips to and from Mars. In particular, studies of human responses to radiation and zero gravity would be conducted. Particles and fields experiments and astronomical observations would also be possible.

A critical requirement for this case study is a heavy lift launch vehicle. Technology requirements are a highly reliable environmental control and life support system, propellant tanks with low inert mass and boiloff rates of cryogenic propellants, propellant transfer capabilities, remote rendezvous and docking in Mars orbit, high-energy aerobrake for Mars capture, hazard avoidance systems for a safe Mars landing, and short-range forecasting technology for solar flares.

Assessment

This case study was a continuation of the FY 1988 preliminary examination of Mars expeditionary requirements, with more in-depth analyses and trade studies of mission options and techniques. A Mars Expedition would offer the national prestige of mounting a mission to land humans on another planet early in the next century. However, significant challenges pervade this approach. The expeditionary pathway emphasizes a major, highly visible effort without the burden and overhead associated with constructing permanent structures and facilities on Mars. Implementation of this approach relies on current or near-term technology and expendable vehicle systems.

Although similar to an Apollo-type mission, the Mars Expedition would, nonetheless, stimulate the development of technological and operational capabilities to test avenues of future expansion of exploration opportunities. In addition to its primary objective, the Mars Expedition would investigate the environment, geology, and materials of Mars that are relevant to the advancement of scientific knowledge as well as the potential for longer-term habitation and resource utilization. This mission could serve as a precursor to future Mars outpost development, and it could help identify prime sites for an outpost as well as return samples of the Martian atmosphere and soil, which could be analyzed for potentially useful resources and the presence of hazardous materials.

* * *

The case study methodology used during fiscal years 1988 and 1989 provided a systematic mechanism for a closer examination of the many pertinent parameters of human exploration of the Moon and Mars. These case studies built directly on earlier analyses conducted in support of the National Commission on Space and the Ride Task Force.

PREREQUISITE PROGRAMS

Both the 1988 and 1989 case studies were deliberately selected to examine a broad range of objectives, options, and requirements. Interestingly, though, all have common characteristics when viewed in terms of prerequisite NASA programs. Two years of intensive study have deepened the understanding of additional investments required in these programs — Earth-to-orbit transportation, human support, robotic missions, and *Space Station Freedom* — to build the vital foundation for human exploration.

Earth-to-Orbit Transportation

Perhaps the most obvious and fundamental requirement for human exploration missions is the ability to launch personnel and equipment from Earth to low Earth orbit, where preparations for subsequent legs of the journey will most likely take place. Although the current Space Shuttle fleet forms the basis of a viable Earth-to-orbit transportation system, the demands of human exploration missions clearly indicate the need for additional, larger payload weight vehicles.

Launching the heavy cargo — propellants, habitats, supplies, rovers, facilities, and scientific equipment — that supports human exploration missions will require launch capacities well in excess of the present Space Shuttle cargo capability. These large mass requirements are a function of both the activity level estimated for building an outpost at a reasonable rate and the ratio of mass in low Earth orbit to mass on planetary surfaces.

Launch requirements as determined by the case studies demonstrate the need for new heavy lift launch vehicles that are able to lift considerably more mass into low Earth orbit than the current Shuttle or Titan IV; otherwise, a single mission to Mars would require dozens of launches per year. The lift capacity of the vehicles must be large enough to reduce the annual launch rate to a reasonable level. Further, trade studies indicate that since payloads must be mated and integrated, it is potentially more advantageous to launch a few large elements for on-orbit assembly than it is to build very many small ones. This approach again requires large launch vehicles.

Analysis has determined launch needs of 60 to 70 metric tons per launch to low Earth orbit for lunar missions and about 140 metric tons per launch for Mars missions, and a number of options exist for meeting these needs (see Figures 1 and 2). For example, a version of the NASA/Department of Defense Advanced Launch System could be designed to support these missions. The Advanced Launch System could have the advantages of low cost per flight, and potentially low life-cycle cost, although development costs may be high compared to Shuttle-C. Launch needs could also be met by a number of heavy lift launch vehicles derived from the Shuttle, modified and enhanced to accommodate the delivery to orbit of much larger payloads. Figures 1 and 2 also illustrate several of these concepts, the smallest of which replaces the nonpropulsive elements of the orbiter with a cargo shroud, and the largest of which is a new assembly of Shuttle components and larger tank elements.

The vehicles on which the 1989 case study development was based are the Shuttle-C for lunar missions and the Shuttle-Z for Mars missions. The Shuttle-C is a conversion of the basic Shuttle into a cargo carrier that can lift approximately four times

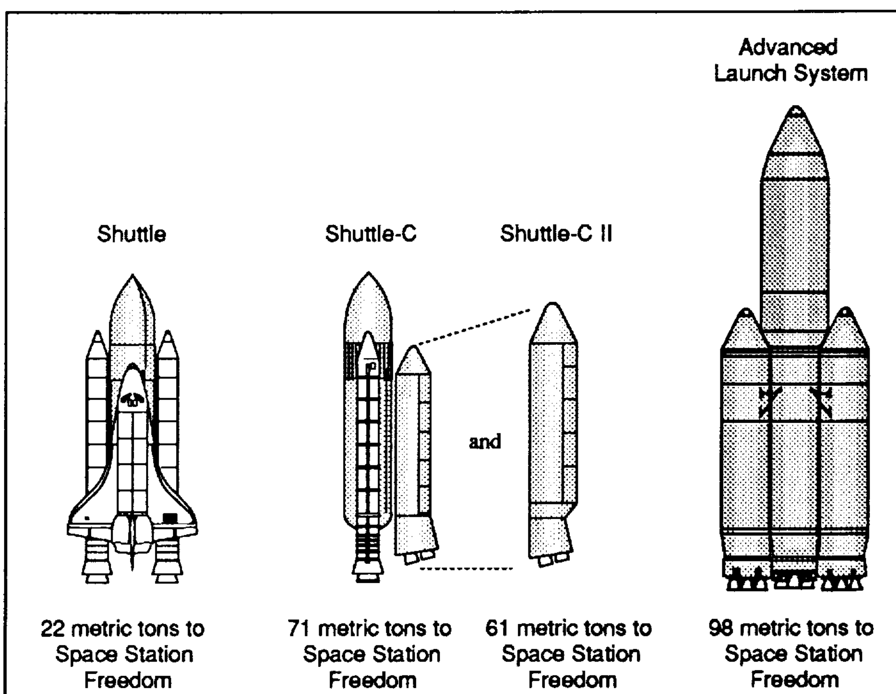

Figure 1. Potential Earth-to-orbit launch vehicles for lunar missions.

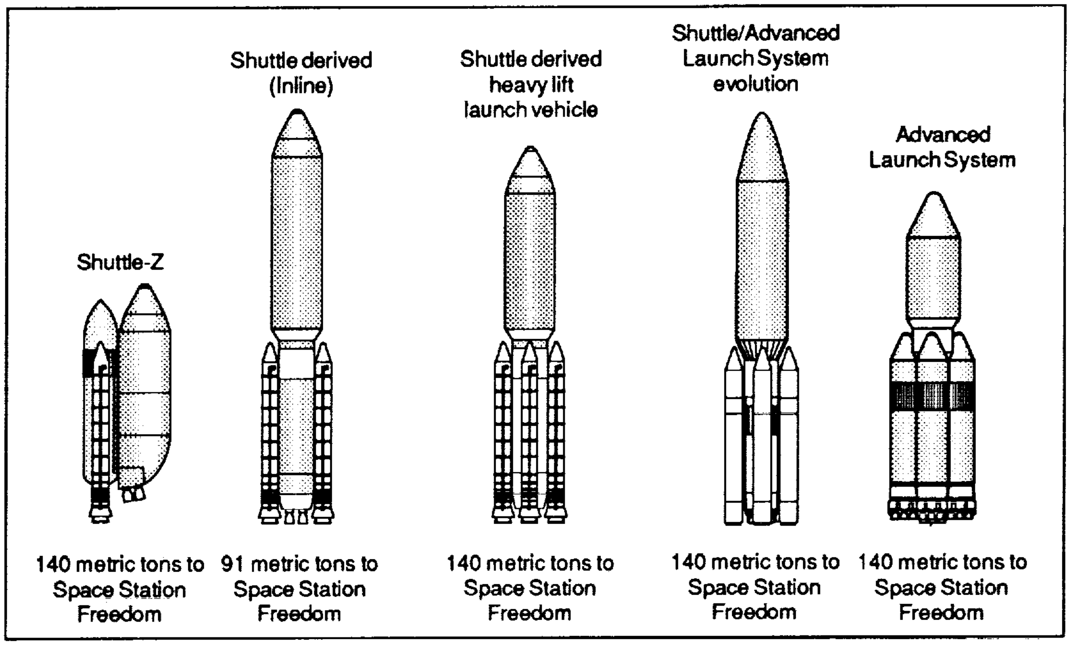

Figure 2. Potential Earth-to-orbit launch vehicles for Mars missions.

as much payload to orbit as the basic Shuttle or Titan IV. The Shuttle-Z is a new concept for growth of the Shuttle-C that integrates the Mars transfer spacecraft and the launch vehicle. The Mars spacecraft's transfer stage is modularized, and one module and the spacecraft itself are placed into a large shroud on what is otherwise a Shuttle-C with a strengthened tank. By utilizing the third stage as part of the payload, the effective performance is almost double that of the Shuttle-C.

Human access to and from space will be supported by the Space Shuttle. With the completion of the new orbiter Endeavour in 1991, the Shuttle fleet will total four vehicles. Because this fleet, combined with expendable launch vehicles, will be serving other national launch needs as well as human exploration, some enhancement will be necessary. As personnel transport requirements are assessed, Shuttle evolution, longevity, fleet size, and availability, as well as future alternatives, need to be examined.

Human Support

Extending human spaceflight mission durations from the Space Shuttle (about a week), to the Shuttle Extended Duration Orbiter (up to 28 days), to *Space Station Freedom* (3 to 6 months), and beyond to extended trips to the Moon and Mars (1 to 3 years) presents unique opportunities and challenges for human support systems. Specific areas of research required for human survival and performance during long-duration spaceflight and extended stays on low-gravity planetary surface areas fall into five primary categories: advanced medical care, countermeasures (including artificial gravity) to mitigate the effects of low gravity, space human factors, radiation protection, and life support.

ADVANCED MEDICAL CARE

Advanced medical care facilities on the Moon and Mars will build on capabilities demonstrated at *Space Station Freedom's* Health Maintenance Facility: outpatient and intensive care, dental care, surgery capability, medical support for emergency return, and hyperbaric treatment for crew members who may suffer "the bends." *Freedom* will also use enhanced ground-based medical operations support, with medical experts on Earth providing crews with computer-aided and "telemedicine" capability for diagnosis and therapy, which will later be applied to medical care at planetary outposts.

Medical care on the Moon will build on ground-based, Shuttle, and *Space Station Freedom* research and experience. Long-duration (6 to 8 hours) extravehicular activity on the lunar surface requires extensive real-time crew health monitoring capability. The medical skills that crew members themselves must have to sustain between 4 and 12 crew members must be defined, in part because transportation of patients between the outpost and Earth will not be simple. Medical needs would be accommodated on the lunar transfer vehicle and the lunar rover by an expanded Shuttle Orbiter Medical System. The lunar habitat would be served by an expanded version of the *Space Station Freedom* Health Maintenance Facility.

Medical care in transit to and on Mars, based on experience gained on the Moon, will consist of a "third generation" Health Maintenance Facility, telemedicine and artificial intelligence medical systems for diagnostics and patient care, and advanced medical care technology demonstrated at the lunar outpost. Planning for health care on Mars is complicated by the fact that life scientists do not know whether hazardous microorganisms or toxic materials exist on Mars, and until robotic sample return missions are completed, our approach will remain undefined. In addition, it is not known whether crew members' susceptibility to illness will alter on return from Mars; therefore, a quarantine program may well be required. Finally, a rehabilitation program for the crew will most likely need to be developed for healthy readaptation after long-duration spaceflight.

COUNTERMEASURES/ARTIFICIAL GRAVITY

Freedom will provide the opportunity to build on experience gained on the Space Shuttle and the Shuttle Extended Duration Orbiter to study and systematically define countermeasures to alleviate the effects of prolonged exposure to microgravity and to maintain, monitor, and protect the health and performance of crews during extended missions. Research is also required regarding physical and psychological rehabilitation for the crew when they return to Earth.

Lunar gravity countermeasures research will build on knowledge gained on the Shuttle Extended Duration Orbiter and *Freedom* to develop and verify specific countermeasures and equipment to enable a 1-year stay on the lunar surface. Additionally, reentry gravity limitations for crews returning to Earth after extended periods on the lunar surface may need to be provided. A quarantine period coupled with rehabilitation also may be required for crew members returning from Mars.

NASA is studying a "dual path" approach to countermeasures and artificial gravity requirements for Mars missions. First, the feasibility of countermeasures to combat the effects of extended exposure to microgravity will be evaluated on *Space Station Freedom*. In parallel, candidate artificial gravity devices will be examined. If artificial gravity is determined to be necessary for maintaining crew health, an artificial gravity research facility in low Earth orbit will be used to demonstrate the technology and systems and study the effects on crew health and behavior. The lunar outpost will also serve as a test-bed to develop and validate systems and procedures prior to the design and development of the Mars transfer vehicle.

SPACE HUMAN FACTORS

Human factors research defines systems, habitats, tools, and procedures that permit self-sufficiency, maintain safety and productivity, and optimize the performance and motivation of crew members while they travel on long-duration space flight missions and inhabit outposts on the surfaces of the Moon and Mars. Current activities to address these needs include the establishment of analogous facilities in remote, harsh environments like Antarctica to conduct ground testing of crew selection, training, small group dynamics, and habitat design. *Freedom Station* will be used as an operational test-bed to refine and verify the procedures and systems developed in the ground-based simulations, and as a precursor to the lunar outpost.

Because tours of duty on the lunar outpost will be longer than those on *Freedom*, human factors considerations are somewhat different. Specific plans to meet lunar outpost needs include the development of high-fidelity simulators of the lunar habitat to conduct systematic testing of protocols, systems, and subsystems. Once established, the lunar outpost itself will be an operational test-bed to refine and verify procedures for the Mars missions, specifically testing the interaction of human factors in a low-gravity environment. Challenges to human factors for Mars missions are similar to those for the lunar outpost and *Freedom Station*, but the longer transit times must be taken into account.

RADIATION PROTECTION

Earth's magnetic field, radiation belts, and atmosphere protect humans on Earth from the damaging effects of space radiation. However, human spaceflight beyond low Earth orbit will entail a high degree of risk from the radiation environment of space. For the lunar outpost, this risk can be substantially mitigated through the use of bagged lunar surface materials to attenuate radiation from space. However, for the Mars transfer vehicle, with its multi-month flights between Earth and Mars, there will be a significant requirement to accurately predict the dose received by crew members and to provide low-mass radiation shielding from solar flares and galactic cosmic rays.

Human missions are currently confined to short-duration Space Shuttle missions in low Earth orbit, where radiation protection is a minimal concern due to the protective character of Earth's magnetic fields. The primary sources of radiation exposure in space are galactic cosmic rays and solar particle events. Requirements for radiation protection will be determined in a number of ways. Ground-based radiation studies will be supplemented with studies using Lifesat, a series of polar-orbiting bio-satellites, to understand the biological consequences of extended exposure to the full spectrum of space radiation. Programs for *Space Station Freedom* focus on determining the biological effects of radiation, minimizing radiation dosage through shielding, countermeasures, and warning systems, and developing radiation standards for exploration missions.

HUMAN SUPPORT RESEARCH CATEGORIES

- ***Advanced medical care***
- ***Countermeasures/artificial gravity***
- ***Space human factors***
- ***Radiation protection***
- ***Life support***

Research for the lunar outpost will determine radiation health standards and shielding requirements for vehicles, habitats, safe havens, and extravehicular activity. Active and accurate forecasting and warning systems for solar particle event exposures will need to be developed, in addition to improved dosimetry to measure a highly mixed radiation field for all aspects of the lunar mission. A radiation risk reduction system will be developed to include partial body shielding, pharmaceutical and nutritional regimes, and a pre-selection program for crew members. Due to the extensive extravehicular activity hours planned for lunar outpost operations, exposure may ultimately result in severe restrictions on crew stay time and/or massive habitat shielding requirements.

The extended exposure of the Mars transfer vehicle to solar radiation as the vehicle travels between Earth and Mars presents significant challenges for radiation protection. Improved mathematical models will be required to accurately characterize the radiation environment. Radiation health standards and shielding requirements for protecting humans and sensitive equipment from all space radiation hazards, as well as shielding requirements for the Mars transfer vehicle, Mars excursion vehicle, habitat, rovers, safe havens, and extravehicular activity operations must be developed. Active, accurate, and reliable forecasting and warning systems must be established to monitor solar particle event activity. Improved dosimetry for measuring radiation exposures within Mars spacecraft, rovers, and habitats must be developed, and a radiation risk reduction system must also be defined.

LIFE SUPPORT

Life support challenges for *Space Station Freedom* that will be relevant to human exploration of the solar system include the development of advanced, reliable life support systems and the development and demonstration of air, water, and eventually food and waste recycling systems. Later, the Controlled Ecological Life Support System test facility planned for *Freedom* will be a test-bed and technology demonstration for the production of food in space.

The presence of a low gravity field, the increased transit time from Earth, and the longer crew tours on the lunar surface may pose additional demands on life support systems for the lunar outpost. Systems and technologies must be defined for lunar extravehicular activity suits, rovers and other surface transportation, and the lunar habitat and safe haven. Since logistics and the resupply of consumables present significant challenges, regeneration of air, food, and water and recycling of waste will be emphasized for the lunar outpost. Permanent human presence on the lunar surface will also challenge environmental monitoring systems to assure the quality and safety of the crew habitat.

Life support requirements for Mars missions reflect the more stringent demands of the length of the mission and the difficulty of resupply. The lunar outpost will provide a test-bed for demonstrating advanced technologies to support these demanding mission needs.

Robotic Missions

Robotic missions to the Moon and Mars will play important roles as forerunners to human exploration, providing information on the planetary bodies themselves and validating the technologies on which human explorers will eventually depend.

Even though both humans and robots have been to the Moon, we need to know more about it before returning to stay. Most of the necessary data requirements will be satisfied by *Lunar Observer*, a spacecraft that is planned for a 1996 launch to map the Moon's minerals and resources. Combined with existing data, the information returned from *Lunar Observer* will help mission designers choose a lunar outpost site most suited for scientific exploration and resource utilization and to plan the exploration of distant reaches of the Moon that will be conducted by astronauts and by robots teleoperated from the lunar outpost and from Earth.

Because our knowledge base of Mars is less extensive, the most intensive robotic activities will focus on Mars. Where should the outpost be located? Does Martian soil pose any hazard to astronauts or equipment? What is the best aerobrake design? These questions will begin to be answered with data from the *Mars Observer*, an orbiter scheduled to be launched in 1992. *Mars Observer* will collect information about the global distribution of minerals and resources important both for planning human exploration and for sustaining long-term human presence. Later in the decade, a proposed global network of geophysical stations — possibly deployed on penetrators — would begin providing information on the planet's interior and on variations in Martian weather. Data from sample return missions planned for early in the next century would provide the means to verify that there are no hazardous materials in the Martian soil. An orbiting camera capable of identifying objects as small as a meter across would help locate safe places for humans to land and to determine the accessibility of the region around the landing site. A key objective of robotic Mars missions will be to provide an engineering design environment data base for Mars spacecraft and surface systems. The robotic Mars missions will also validate technologies, such as aerobraking, pinpoint landing, and automated rendezvous and docking, that are necessary to land astronauts and equipment on Mars and return them to Earth.

Finally, for both the Moon and Mars, robotic missions also provide opportunities to advance science and expand the foundation of international cooperation.

Space Station Freedom

This permanent facility in low Earth orbit is an important prerequisite for human missions to the Moon and Mars. It will serve first as a human support research facility where we will gain knowledge essential for long-duration missions in low gravity environments and develop related technologies for future missions. Later, evolved versions of *Space Station Freedom* may be used to assemble, check out, and launch lunar and Mars vehicles. The hardware "hooks" and software "scars" that will enable this evolution of *Freedom Station* must be preserved as part of its design.

The case studies were varied to place different demands on *Space Station Freedom*, and this has aided *Freedom's* designers as they build a baseline facility with the ability to evolve to meet future mission requirements. Precursor research and technology development, as well as mission staging to be done on *Freedom*, are schedule drivers for human exploration.

Resources available to researchers on *Freedom* include power, pressurized and unpressurized volume to conduct experiments, data management and communications systems, thermal environmental control, robotics, machine intelligence, and — the most crucial resource — trained men and women. Logistics flights will provide a thin umbilical to Earth as full-scale manned operations in space are conducted on a day-to-day basis.

If *Freedom* is to serve as an exploration research center and/or transportation node, significant augmentations to the resources and capabilities initially provided by *Freedom* are needed for human exploration missions. The 1989 Lunar Evolution case study typifies these requirements. The lunar case requires that 150 kilowatts of power in the form of solar dynamic concentrators be added to the baseline *Freedom Station*. Crew requirements, including mission personnel and *Freedom*-based research and support crew, escalate from eight to as many as 18 people, necessitating one additional habitation module. If Mars is the destination, one laboratory module will most likely be dedicated to research into basic biological processes and clinical medicine to answer the questions of how we must adapt to live and work productively in this new environment. The transportation node also features more truss to create the space and attachment points for the space transfer vehicle processing facility.

Various *Space Station Freedom* evolution configurations that can satisfy the requirements of the exploration missions are being analyzed to produce an optimized design solution. The evolution reference configuration provides a "target" for the systems engineers as they ensure that the baseline design can evolve to a transportation node. The final reference configuration will include an operations concept to determine compatibility among baseline missions in microgravity research, payload servicing, stellar and Earth viewing, and the evolutionary transportation node functions.

In addition to structural enhancements, essential distributed systems, such as propulsion, data management, communications and tracking, guidance, navigation, and control, thermal control, fluid management, mechanical systems, and electrical power systems, must also have the ability to evolve. Considerable effort has been made to understand the "systems level" implications of supporting human exploration missions.

One such effort was to determine the impact associated with adding the function of on-orbit vehicle processing to *Freedom*. Both the lunar and Mars missions may require on-orbit vehicle processing due to large mission mass, constrained Earth-to-orbit lift capability, and reusable vehicles. By utilizing known hardware and processing times at the Kennedy Space Center, a detailed space transfer vehicle ground processing flow was developed to examine these procedures. On-orbit processing flows are derived from the ground flows by selecting only those tasks that must be performed at *Freedom*. This technique permits determination of on-orbit timelines, manpower needs, and resources required from each system for on-orbit vehicle processing. Ongoing work will match historical extravehicular/intravehicular activity times to the on-orbit processing tasks. Also, an automation and robotics "scrub" will be performed on the processing flows to apply technology to reduce crew risk and minimize extravehicular activity. These flows will result in a set of evolution resource requirements and recommended design provisions, by system, for inclusion with the evolution reference configuration.

Technology must also evolve in order for *Freedom* to function as a transportation node. Three primary areas require advancement: in-space vehicle processing and refurbishment, in-space assembly and construction, and cryogenic fluid management and transfer. *Freedom* will be the test-bed for precursor demonstrations in these areas before actual application during piloted missions. Possible evolution schemes for *Freedom* are discussed in detail in Volume IV of this document series.

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Prerequisite programs in Earth-to-orbit transportation, human support, robotic exploration, and *Space Station Freedom* form the very foundation for human exploration of the Moon and Mars. These programs represent areas in which definition must be completed in advance of program implementation and vehicle design. The capabilities of Earth-to-orbit vehicles will drive the way that payloads are developed, allocated, and packaged. Human support research must be completed to support the design of spacecraft and support systems for transfer vehicles and planetary habitats. Robotic missions are necessary to support the planning of the human missions. And *Space Station Freedom* is important for any human missions. In this manner, these prerequisite programs pave the way for the definition and implementation of the human exploration program.

TECHNOLOGY

An essential element of NASA's charter is to pursue the development of advanced technologies, which enable both progress in the exploration of space and improvement in the quality of life here on Earth. This goal has been repeatedly reaffirmed in National Space Policy Directives issued over the years. Yet studies assessing the future direction of the U.S. civil space program have concluded that our technology reservoir must be replenished in order to enhance our range of technical options to ensure continued U.S. leadership in space.

Historically, one of the benefits of exploring space has been the development of a technology base that strengthens the Nation. Application to the private sector of technologies developed for the space program enables the United States to compete more effectively in the increasingly technological global community. Sophisticated human exploration missions will contribute substantially to our technology base because this program will require and stimulate the development of advanced technologies in many areas. Because the period between initiation of technology development and readiness for actual mission application can run into many years, determining technology needs well in advance is imperative.

The case study methodology employed by the Office of Exploration from 1987 through 1989 was structured specifically to isolate technologies that enable or enhance human exploration of the Moon and Mars. Special emphasis was placed on identifying technologies that are required for or that would significantly increase the capability or decrease the cost of a particular mission. In addition, the time phasing and development requirements and risks associated with each technology were examined. Focusing on these two aspects has allowed an understanding of the implications of programmatic decisions regarding technologies to select or preserve as future options. More detail on technology studies is provided in Volume V of this series.

Of course, much work remains to be done. Technology development and the continued pursuit of innovative approaches will be a principal focus of our early efforts in setting out a program to return to the Moon and journey to Mars.

Prior to the landing of the first system for the lunar outpost, one or more orbital missions may be launched to survey the Moon for resources and to certify the landing site. The current reference mission to meet this need, the *Lunar Observer*, requires no notable new technology developments.

Concurrent with the *Lunar Observer* and the establishment of the lunar outpost, a series of robotic missions to Mars will develop the scientific, engineering, and technology foundation upon which subsequent human missions will be based. These missions require a variety of major technological developments. A global network on Mars will require durable power supplies, impact-tolerant electronics and instruments, and the technology for deep subsurface penetration. The return of samples from specific sites on Mars mandates capabilities for autonomous landing, rendezvous, and docking, and techniques for sample acquisition, analysis, and preservation. Extended-range rovers on Mars need mobile power, onboard and ground-based automated operations, and mobility. Aerocapture at Mars requires advances in aerothermodynamic modeling of the Martian atmosphere, thermal protection systems for the aeroshell, and adaptive guidance, navigation, and control.

Establishing a long-term lunar outpost will require major advances in engineering capabilities in lunar surface systems, transportation, and low Earth orbit operations. Innovative lunar surface systems will require development of technologies for low-cost, highly reliable life support, extended extravehicular activity, and high-capacity power generation at the lunar surface, including generation of power during the 354-hour lunar night. Transportation and in-space operations will involve a family of closely coupled systems: Earth-to-orbit transportation systems, *Space Station Freedom* elements, and space-based vehicles for transportation to the lunar surface. Techniques will be needed for in-space cryogenic propellant handling, storage, and transfer, and for vehicle assembly and processing at *Space Station Freedom*. Technology must also be developed to automate the planning and execution of outpost operations, information processing, software engineering, and training techniques.

Human exploration and settlement of Mars will build directly on the technologies developed for and proven during the robotic Mars and lunar outpost missions. Sending humans to Mars will mandate developments in almost all areas of technology. In particular, major advances will be required in life support for the Mars transfer vehicle and habitats, space transportation, in-space operations, and surface systems.

Technology requirements that apply to more than one mission element include substantial increases in ground and surface operations automation; in-space system autonomy; diverse applications of advanced electromechanical manipulator systems, using control approaches ranging from teleoperation, through telerobotics, to full robotics; and requirements for data and control system components and software that increase the fault tolerance of system operations, including automated fault detection, isolation, and resolution. Across all phases of the Space Exploration Initiative, human safety and health during long-duration missions will have high priority and will pace and direct technology development.

Critical Technologies

A major challenge of human exploration of the Moon and Mars is the need to dramatically decrease the total mass that must be launched into low Earth orbit and transported to the lunar and Martian surfaces. Although additional factors, such as crew time, power, and servicing requirements, are very important, reducing launched mass is an overarching need for long-term self-sufficiency and acceptable operations costs. In addition to judicious application of lightweight materials, such as those being examined in connection with the National Aero-Space Plane, critical technologies in regenerative life support, aerobraking, and advanced space-based cryogenic engines must be developed to substantially reduce the mass of near-term systems. Mid-term technologies critical to decreased mass are surface nuclear power, in situ resource utilization, and radiation shielding. In addition, although human expeditions to Mars can be conducted using cryogenic propulsion and aerobraking, nuclear propulsion presents a compelling prospect for greatly reducing the mass or travel time required.

REGENERATIVE LIFE SUPPORT SYSTEMS

The piloted vehicles and pressurized surface systems planned for use on the Moon and Mars will require life support systems with varying degrees of capability. For the lunar outpost, short-term life support will be required for the lunar transfer and excursion vehicles. Long-term life support will be required for both emplaced and constructed lunar habitats, as well as for the Mars transfer vehicle.

Numerous factors of outpost operations preclude long-term reliance on Earth-based servicing; for example, the costs of transportation to a lunar outpost, the length of Earth-Mars transits, and the duration and remoteness of Mars surface operations. Regenerative life support systems will provide enormous mass savings for exploration systems and operations. In situ recycling of life support resources, especially air and water, could reduce the launch mass by 20 kilograms for each crew member each day of the mission.

Research and technology development for both physical-chemical and bioregenerative life support systems is in progress. Because of the time required to achieve technological maturity, early lunar outpost elements may rely heavily on physical-chemical life support systems derived in large part from *Space Station Freedom* systems. The initial lunar outpost habitat may be equipped with more technologically advanced systems. Concurrently, life support research and technology development for Mars-mission vehicles and surface systems can achieve required levels of maturity.

Regenerative life support systems for constructible habitats, planned for use on both the Moon and Mars, can incorporate improved technologies that enable high levels of closure, high reliability, and in situ maintenance and repair. These improvements will reduce operations costs and mission risks.

To improve current and projected life support systems, technology development is needed in the critical areas of air revitalization, water purification and/or reclamation, waste management and processing, air and water quality control, and sensors and processors for reliable environmental monitoring and autonomous operations. All systems must be designed for high reliability, in situ maintainability, and a high degree of system autonomy. Complete closure of the life support system for long-duration human surface operations on the Moon and Mars will, of necessity, require local food production. Although not critical to the early phases of the program, complete closure is a major strategic program option enabling long-term inhabited outposts. NASA is currently researching controlled ecological life support systems to determine their feasibility, and is beginning to plan for eventual integration of bioregenerative life support sub systems into physical-chemical life support systems.

AEROBRAKING

Aerobraking is a technique that uses the atmosphere of a planet to decelerate a spacecraft and change its trajectory, instead of using propellants carried all the way from Earth to achieve the same results. An aerobrake is considered low- or high-energy depending on the incoming velocity of the spacecraft on which it is mounted and the resultant heat generated by deceleration. Aerobraking is needed for space transportation for the lunar outpost missions, robotic Mars missions, and human flights to Mars; thus, reusable aerobrakes might provide substantial total cost savings. Experience in low-energy aerobraking is derived from the Apollo program and current experience with Space Shuttle flights. However, this experience covers only simple blunt configurations operating in a narrow corridor; these programs have yielded very limited data relative to in-space aerobraking. For high-energy aerobraking, Apollo-era ablative thermal protection materials represent the state of the art. These materials are inherently heavy and cannot meet desired design goals. Although not a definitive requirement, high-energy aerobraking, especially for the return to Earth from Mars, is a significant option that could further reduce the weight of the flight systems.

CRITICAL TECHNOLOGIES

- *Regenerative life support systems*
- *Aerobraking*
- *Cryogenic hydrogen-oxygen engines*
- *Surface nuclear power systems*
- *In situ resource utilization*
- *Radiation protection technology*
- *Nuclear propulsion*

Efforts are underway within NASA to develop the technologies needed for aerobraking. Within the Civil Space Technology Initiative, the Aeroassist Flight Experiment will provide in-space validation of computer models by the mid-1990s. An integrated technology program for interplanetary aerobraking, in particular, for high-energy aerobraking, is also in progress.

CRYOGENIC HYDROGEN-OXYGEN ENGINES

Advanced cryogenic hydrogen-oxygen propulsion systems will be required for human exploration missions. The most important of these is the moderate-thrust (90 kilonewton class) engine with a specific impulse of about 480 seconds for the lunar transfer vehicle and 460 seconds for the lunar excursion vehicle. Related technology developments in high-thrust (e.g., 900 kilonewtons) cryogenic engines and in integrated, cryogenic attitude-control thrusters will be needed for the Mars transfer and excursion vehicles. Critical design developments include space-basing, high thrust, throttling (for landers), reusability without servicing at *Freedom* or on the Moon, and small engine size for aerobrake compatibility.

Building on its foundation of basic research and technology development in engine components, NASA has initiated a program to integrate early component-level technology into breadboard engines, including that for essential throttling and in situ engine-health monitoring capabilities.

SURFACE NUCLEAR POWER SYSTEMS

As initial lunar outpost systems evolve toward more permanent installations, requirements for power will grow. Photovoltaic arrays and regenerative fuel cells can provide lower levels of power, but they require relatively frequent system maintenance and significantly more mass than space nuclear power systems, especially on the Moon with its long nights. A space nuclear power system would provide power in the 100-kilowatt range, limited total system mass, long life, and high reliability. For production of 100 kilowatts of power at the lunar outpost, a nuclear system would provide a savings of more than 300 metric tons in initial mass in low Earth orbit when compared with advanced photovoltaic arrays and regenerative fuel cell energy storage. Beginning with the early part of the consolidation phase of the lunar outpost, nuclear reactors offer the only cost-effective approach to providing high levels of continuous power for the lunar outpost. In the far term, surface nuclear power may provide the long-lived, highly reliable power necessary for Mars surface systems.

The state of the art in space nuclear power systems is represented by radioisotope thermoelectric generators that typically provide about 250 watts of power. However, research programs in progress will lead to more powerful systems. The SP-100 program, sponsored jointly by NASA, the Department of Defense, and the Department of Energy, will provide ground validation of a space reactor system and technologies yielding thermoelectric conversion efficiencies of approximately 3 to 4 percent. Those advances will make possible a space reactor power system that produces about 100 kilowatts of power and has a projected system lifetime of 7 to 10 years. Another NASA research and technology development program has the objective of producing more advanced subsystems for thermal-to-electric conversion. The evolution of such systems can provide the megawatt capability that will be required if lunar resources are to be used to offset Earth-based logistics support.

Key areas for technology development in the SP-100 program include the space reactor system, thermal control systems, and thermal-to-electric conversion technologies including solid state thermoelectric converters and dynamic conversion systems such as Stirling engines, and thermal control systems.

IN SITU RESOURCE UTILIZATION

The use of nonterrestrial resources can substantially benefit a variety of future space activities by dramatically reducing the amount of material that must be transported from Earth to a planetary surface. For example, through the processing of lunar rocks and soil, liquid oxygen could be produced for propulsion and life support, and the lunar soil could be a source of materials for construction and radiation shielding. In situ resource utilization will rely on technology development in resource processing and mining and beneficiation. Substantial application of robotics to mining and handling equipment and of automation to processing equipment will be critical.

Although resource processing has been the subject of considerable study, very little technology has been developed for nonterrestrial utilization of in situ resources. Lunar samples have been studied extensively, and several processes have been proposed for producing lunar oxygen and other materials, such as ceramics, metals, and construction components. The most promising of those processes are based on either chemical-thermal or electrolytic processes. However, little process engineering has been done to date, and no single process can be considered to be proven for long-term use in the lunar outpost.

Earth-based mining and beneficiation equipment is typically very massive, requires routine servicing, and employs high levels of mobile power. Some degree of automation is being implemented in terrestrial mining operations, but it is unclear whether systems for long-term lunar use can be derived directly from Earth-equipment experience. Beneficiation concepts, including electrostatic and magnetic separation, have undergone some laboratory experimentation. On the positive side, early results suggest that low gravity and low electrical conductivity may actually improve process performance and reduce system mass and power requirements.

A significant percentage of the propellant mass required for Earth-Moon transportation systems is oxygen, which is also the principal constituent of the lunar soil, at about 42 percent. Although precise specifications vary, a typical objective for lunar outpost in situ resource utilization would be to produce approximately 50 metric tons of liquid oxygen per year to be used in lieu of liquid oxygen brought from Earth for use in lunar-based transportation systems. Given a full-scale production plant with a mass of approximately 50 to 100 metric tons, the payback period in terms of simple mass to the lunar surface could be 1 to 2 years, depending on final production requirements.

Processes for extracting Martian resources are believed to be much simpler, because oxygen could be produced through straightforward reduction of the atmosphere, which is primarily carbon dioxide. Mining and beneficiation requirements for Mars have not yet been defined.

RADIATION PROTECTION TECHNOLOGY

Although tons of soil may be used indefinitely to provide shielding for stationary objects on planetary surfaces, crews in transit between Earth and Mars must also be protected, and each pound of in-transit shielding entails an enormous penalty in initial mass in low Earth orbit. Only through an accurate understanding of the radiation present and of radiation protection techniques can the actual amount of shielding required to ensure the long-term health and safety of crew members be determined.

There is a critical need to confidently predict, within 10 percent, the shielding capabilities of various materials and spacecraft components. In addition, research and technology development is needed for lightweight shielding techniques and materials that will ensure adequate protection for crews during Earth-Mars transits. NASA is planning a significant, focused program to provide research results to support Mars transfer vehicle development and possible upgrades of initial lunar outpost systems.

NUCLEAR PROPULSION

Detailed mission planning for human exploration has centered on the use of high-performance cryogenic engines and aerobraking technologies as the foundation for Earth-Moon and Earth-Mars transportation. However, the high-performance propulsion capabilities that can be provided by non-chemical, nuclear energy-based systems could substantially reduce launched mass requirements and flight times to and from Mars.

Nuclear thermal rockets use a nuclear reactor to directly heat a working propellant for moderately high specific impulse, very high thrust propulsion. Potential classes of such nuclear thermal rocket propulsion systems include solid core, liquid core and gaseous core nuclear reactors. Of these, solid core reactor systems have the greatest level of technological maturity (they are based on extensive development conducted during the 1960s and early 1970s). However, gas core nuclear thermal rockets promise the greatest potential mission benefits, in terms of dramatically reduced flight times and somewhat reduced initial launched mass requirements.

Nuclear electric propulsion concepts employ a nuclear reactor to generate the electricity that is used to drive electric thrusters for very high specific impulse, low to moderately high thrust propulsion. Nuclear electric propulsion systems promise the greatest potential mission benefits in terms of dramatically reduced initial launched mass requirements, with the potential for moderate improvements in Earth-to-Mars flight times.

SCIENCE

Human exploration of space is not motivated principally by science. National pride, international prestige and leadership, and economic, technological, and educational competitiveness all play at least as large a role as science in national decisions on human exploration programs. Yet scientific research is now and will continue to be a central activity of humans in space, for space provides profound opportunities to advance knowledge.

Although much information has been and will continue to be gained through robotic exploration missions, humans have capabilities for conducting detailed field studies and for constructing large scientific instruments, such as arrays of large optical telescopes on the Moon, that are far beyond the scope of robots. Ultimately, solar system exploration science will be advanced through a combination of robots and humans, working together to push back the frontiers of knowledge. The disciplines that will be advanced are diverse, including geology and geophysics, planetary meteorology and climatology, astronomy and astrophysics, particle and solid state physics, exobiology, human and plant physiology, and evolutionary biology.

Consider Earth's satellite, the Moon. The Moon is thought to have formed from material spewed into space when a Mars-sized body slammed into the infant Earth. Study of the Moon may thus have much to tell us about the earliest days of our own planet. A lunar outpost would be a staging point for humans to conduct geologic field studies that would address these and other fundamental questions raised by the Apollo missions. Was the Moon ever covered by a global ocean of molten rock? Does it have an iron-rich core like Earth? For some studies, humans might travel to the far reaches of the Moon; for others, telerobots would be operated from the outpost or from Earth. The wealth of gathered samples could be screened in a lunar laboratory, the most valuable being sent to Earth for detailed analysis.

Geologic studies would also clarify the history of impacts that have scarred the lunar surface and perhaps modified life on Earth. The lunar maria (vast plains of solidified lavas) contain a record of impacts over the last 3 to 4 billion years. It is widely believed that the demise of the dinosaurs and other great terrestrial extinctions were caused by enormous impacts. If so, we might find a correlation between those extinctions and the rate and nature of lunar impacts, a result that would profoundly affect our views of how life—including human life—has evolved and would help determine whether such events are cyclic, as some scientists believe.

The Moon is also a valuable platform for studying distant stars and galaxies, the rest of the solar system, and planets around other stars. The Moon's airless, seismically stable environment is an ideal location for a large array of telescopes that would yield incomparably sharp pictures of distant galaxies. An array of antennae on the lunar farside could yield a radio-frequency view of the universe, unhindered by natural and artificial radio noise from Earth. An infrared telescope, naturally cooled in permanent shadows at the lunar poles, would have exceptional sensitivity for observing dust and molecular clouds.

Instruments on the Moon could measure the solar wind while lunar telescopes and Earth-orbiting satellites observe terrestrial auroras, helping us understand the interactions of Earth with its interplanetary environment.

Lunar soils once on the Moon's surface, but long since buried by lava flows and impact debris, preserve a record of the solar wind to which they were exposed. Careful excavation of these soils would provide glimpses of the ancient Sun, improving our knowledge of stellar evolution and the history of the Sun's influence on Earth. Lunar materials currently exposed to the solar wind are a storehouse of hydrogen and other volatiles for use by lunar explorers.

The Moon is also a natural laboratory. For example, medical studies of humans living on the Moon would tell us whether 1/6 g is enough gravity to eliminate the harmful effects of weightlessness. The absence of strong magnetic fields at the Moon makes it a natural physics laboratory for experiments, such as measurements of the neutron's electric dipole moment, that are limited on Earth by variations in Earth's magnetic field. On Earth, cosmic rays striking the atmosphere produce particles that limit physicists' ability to detect rare events, like proton decays and neutrino interactions. The airless Moon will permit vast improvements in these measurements. Science on the Moon will thus involve study of the Moon itself, as well as use of the Moon as a platform and laboratory to study other objects.

On Mars, science can be similarly diverse, but Mars' geologic variety and its unique role as a possible habitat for life will lead to a focus upon whether life has ever existed on Mars and how the planet's geology and climate have evolved over the lifetime of the solar system.

Few discoveries would have more impact than the discovery of extraterrestrial life. We know that life on Mars is unlikely under today's surface conditions. Indeed, the *Viking* landers did not find evidence of life, nor did they even find evidence of organic compounds that are a part of all living systems on Earth. But these results do not mean that life has never existed on Mars, and they do not even preclude life on the planet today. Determining whether life on Mars extant or extinct, was fundamentally similar to or different from the type of life that exists on Earth, would be of profound significance.

The possibility of life on Mars stems from the planet's warm, wet past. The evidence for this early, more clement period is striking. Ancient cratered highlands that make up nearly two-thirds of Mars' surface are covered with channels that resemble terrestrial river valleys. Younger regions of Mars show evidence of vast floods. Together, these observations suggest that Mars may have had abundant water, and that the atmospheric pressure and temperature were once high enough to allow it to exist as liquid on the planet's surface.

It thus appears that early conditions on Mars may have been similar to those on Earth. Could life have formed during this benign climatic period in Martian history? We know that life on Earth formed very early. The oldest terrestrial fossils are stromatolites—remnants of microbial colonies that existed at least 3.5 billion years ago. Life must have formed on Earth even earlier, at a time when Martian and terrestrial conditions were similar. Even though there is much uncertainty about how life formed on Earth, the early of the two planets suggests that life may have formed on Mars as well.

It is even possible that life exists on Mars today in underground habitats where volcanic heating melts ground ice, producing a warm, wet environment protected from the harsh surface conditions. Bacteria live in such habitats on Earth with no access to sunlight. Might these be the last refuge of ancient Martian life?

The great Martian climate change raises a question central to concerns about Earth's environment. What causes global climate change? There is strong evidence that human activities are affecting Earth's climate today. But Earth also underwent climate change before humans appeared on the scene. Climate change of any type — natural or anthropogenic — can have great impact on society. Mars provides a second planetary laboratory for our study of global climate change.

Mars's climate change is one aspect of evolutionary processes that have produced a planet of fascinating geologic diversity. The great system of canyons that stretch 5,000 kilometers along the Martian equator could encompass Arizona's Grand Canyon as a small tributary. The western end of the canyon system merges into the Tharsis dome, a vast, upthrust region dotted with enormous volcanoes. Toward the north, great plains circle the planet, forming a low-lying debouchment for floods that originated in the ancient, cratered highlands. Ice caps at both poles show layering caused by periodic atmospheric changes. The study of this geologic diversity is intimately related to the study of Martian climate change and the search for evidence of life. Together these endeavors will form the scientific core of the human exploration of Mars.

To understand in more detail how human explorers will address these scientific questions, the Office of Exploration has supported a number of science workshops and analyses during the past year. These studies were closely coordinated with, and sometimes cosponsored by, NASA's Office of Space Science and Applications.

The objective of these studies was to define the scientific goals of human exploration missions and the means by which those goals would be achieved. An additional objective was to understand the design of exploration programs comprising both robotic and human missions, and to understand how robots can assist human explorers. The results formed the basis for the science content of the three case studies investigated during 1989. Such efforts will continue to be an important element of future planning for human exploration missions.

INNOVATIVE OUTREACH PROGRAMS

A fundamental NASA tradition has been to encourage innovation. In keeping with this tradition, the Office of Exploration initiated several activities early in 1989 to encourage innovative concepts and support independent studies in specialized areas that may offer unique capabilities for human exploration. These activities were to focus on specific technical areas that were out of the mainstream of traditional NASA research, or to search for new concepts and ideas. Innovative studies in 1989 encompassed three areas: (1) an innovation outreach program, (2) a lunar enterprise study, and (3) a lunar mining study.

Initiated prior to the President's speech in July 1989, the "Innovation Outreach" program was designed to solicit and advance original, creative ideas from traditional sources, such as the aerospace industry and academia, and non-traditional sources, such as medical, mining, or other non-aerospace firms. This program supported the study of new, unconventional, or overlooked techniques in engineering and applied technology. To this end, a NASA Research Announcement was released in April 1989 requesting ideas, devices, concepts, systems, orbital trajectories, operations, or implementations that could further human exploration of the solar system. One restraint was that NASA would consider proposals only for those ideas that could feasibly result in flight systems by the year 2025.

More than 100 proposals were submitted, and selections were made in July 1989. The 21 proposals selected for funding came from groups located in 12 states and from various occupations, with five industry-related firms, two space support-related organizations, and 14 universities. The subject matter of the selected studies, funded for a 1-year period, ranged from nuclear thermal rockets using Martian propellants to pneumatic structures for lunar and Martian habitats. The titles of these awards are listed in the table on the next page.

The second of the 1989 innovative studies, the Lunar Enterprise Task Force, was conducted to provide an outside perspective on the commercial uses of the Moon. The envisioned potential benefits would be two-fold — the provision of a low environmental impact energy source for commercial use on Earth, and increased lunar outpost self-sufficiency.

The task force, composed mainly of non-NASA individuals from the power industries, utilities, financial community, economists, physicists, and construction/mining companies, was asked to determine the economic viability and commercial potential of extracting materials from the Moon for use in generating electrical energy on Earth. Three plausible energy production techniques were examined: (1) mining and extracting helium-3 for export to Earth for powering ultra-clean fusion reactors in the next century; (2) using a solar power satellite, constructed of materials from the lunar surface, to transmit energy to Earth from Earth orbit; and (3) developing a solar power system made of lunar materials to transmit energy from the lunar surface to Earth. Techniques and systems for transferring materials and energy from the Moon and Earth orbit were examined in this context, as were the economics, legal parameters, technical skills, and time frame of the three ventures. The possible roles of government and international agencies and other concerns were also debated.

The main conclusions of this task force are startling and visionary: the Moon, contends the Task Force, must play a major role in supplying energy to Earth in the next century; and there is sufficient helium-3 on the Moon to supply all Earth's electrical energy needs for thousands of years. Also fortunately, the time scale of the likely availability of commercial fusion reactors appears to match that of the ability of a lunar outpost to sustain large-scale mining operations. All three concepts — helium-3, solar power satellites, and lunar-based solar power systems — were found to be viable energy sources, with the caveat that lunar-based solar power systems are the most complex and will require additional study. Further deliberation led to the conclusions that, for such ventures to be successful, innovative approaches to private and public cooperation, technical development, and financial sources, would need to be implemented, and that a combined government and industry venture might very well flourish in the long term. An appropriate next step could be a joint venture with industry to determine the feasibility of mining helium-3, as well as other materials, during the early phases of the lunar outpost.

The third 1989 innovative study, a subset of the "lunar enterprise study," was aimed at defining a lunar mining system and the infrastructure required to make such a facility operational. A long-term evolutionary program to explore and settle the inner solar system would ultimately require a functional, self-sufficient lunar outpost. One aspect of self-sufficiency entails mining the lunar soil to obtain materials for construction, oxygen extraction, rocket fuel, and shielding. Noteworthy experts in the fields of mining and construction were called upon to coordinate this study. This outside expertise, in conjunction with the Office of Exploration, was directed to examine several key issues related to a lunar mining facility.

The objectives were to (1) identify the parameters governing the development of a lunar mining system, particularly infrastructure requirements for personnel, equipment, and power; (2) examine various known mining methods and develop a lunar mining model; and (3) formulate an analytical report on the results. The lunar mining study concluded that many terrestrial automated mining and processing methods could be applied to lunar oxygen production, which would eliminate the need for any great technological leaps and would lead to earlier lunar oxygen production and possibly other early lunar resource utilization. The next step is to further determine the specific infrastructure requirements for a long-term space program plan.

INNOVATIVE STUDY AWARDS: 1989

Space Support-Related Organization Winners

- Oregon L-5 Society, Inc., Oregon City, Ore. - "Site Characterization of the Oregon Moonbase."
- Tether Applications, La Jolla, Calif. - "Preliminary Design of a 1 KM/SEC Tether Transport Node."

Industry-Related Winners

- Martin Marietta Strategic Systems, Denver, Colo. - "Study of Nuclear Thermal Rockets Utilizing Indigenous Martian Propellants."
- Dean & Associates, Alexandria, Va. - "An Early Warning System for Monitoring Large Projects."
- Titan Systems, Inc., San Diego, Calif. - "The Evolution of Design Alternatives for the Exploration of Mars by Balloon."
- Engineering Development Laboratory, Inc., Newport News, Va. - "Determination of the Concentration of Spacecraft Cabin Gases using Laser Spectroscopy."
- Orbitec, Madison, Wis. - "Aluminum/Oxygen Rocket Engine for Lunar Transport Applications," and "The Use of Tethered Platforms to Recover, Store, and Utilize CO_2 from the Mars Atmosphere for On-Orbit Propellants."

University-Related Winners

- Energy & Mineral Research Center, Grand Forks, N.D. - "Further Investigation of the Feasibility of Applying Low-Temperature Plasma Technology to a Closed-Loop Processing Resource Management System."
- Texas Engineering Experiment Station, College Station, Texas - "Design of a General Purpose, Mobile, Multifunctional Radiation Shield for Space Exploration."
- Boston College, Chestnut Hill, Mass. - "Design Considerations of a Lunar Production Plant."
- Michigan Technological University, Houghton, Mich. - "Planetary Materials and Resource Utilization."
- The Regents of the University of California, Santa Barbara, Calif. - "A Small Particle Catalytic Thermal Reactor (SPCTR) for the Conversion of CO and CO_2 to Methane in a Gravity-Free Environment Vehicle."
- The University of Michigan, Ann Arbor, Mich. - "Advanced Fuel Cycles for the MICF-Fusion Propulsion System."
- Boston University, Boston, Mass. - "Pneumatic Structures for Lunar and Martian Habitats."
- State University of New York at Stony Brook, Stony Brook, N.Y. - "Artificial Intelligence to Simulate the Green Thumb."
- The Regents of the University of Colorado, Boulder, Colo. - "Mars Tethered Sample Return Study."
- The University of New Mexico, Albuquerque, N.M. - "Teleprospector: A Teleoperated Robotic Field Geologist."
- Duke University, Durham, N.C. - "Deployable Magnetic Radiation Shields Using High Tc Superconductors: A New Concept."
- International Space University, Boston, Mass. - "International Lunar Polar Orbiter (ILPO)."
- The University of Texas, Houston, Texas - "Emergency Surgery and Surgical Critical Care to Support Human Exploration of the Solar System."

CONCLUSIONS AND RECOMMENDATIONS

In 1988 and 1989, NASA studied the ways in which this Nation might achieve human exploration of the Moon and Mars. To examine the feasibility and implications of several approaches, we developed seven case studies that followed three different types of strategies: expeditions, scientific outposts, and evolutionary scenarios. To thoroughly understand how we might achieve early leadership in human space travel, we carried an expeditionary philosophy through three different journeys: to Phobos, to Mars in two stages and three visits, and to Mars in one stage with one visit. Recognizing that a stable, long-term outpost on an extraterrestrial body would tremendously enhance our scientific knowledge, we studied a lunar observatory. And finally, the evolutionary approach was developed in three different forms: a lunar outpost that leads to a Mars outpost, a three-phase development of a lunar outpost, and the same three-phase development of a Mars outpost.

By examining key aspects of these case studies — interplanetary trajectories, launch vehicles, transportation nodes, space transfer vehicles, and planetary surface systems — we came to better understand what is required in each of these areas. An interdisciplinary study team has begun research to characterize the human aspects of long-term space travel and settlement: the psychological and physiological effects and the ways in which they might be avoided or ameliorated. The robotic precursors of human explorers have been studied to determine how they will provide the scientific, engineering, and environmental information that is so vital to an overall landing and operational strategy. And finally, scientists have defined an abundance of ways in which human explorers will enhance scientific knowledge.

Technical and programmatic analyses of the case studies lead to the following basic conclusions.

- *SPACE STATION FREEDOM* may be necessary for voyages to the Moon and Mars. It is the key to developing the capability to live and work in space for much longer periods than we do now. Because logistics flights to low Earth orbit are expensive, a transportation node in low Earth orbit may be found to be necessary as flight rates increase. Future human exploration mission plans may depend heavily on *Freedom* as this transportation depot in Earth orbit. The development, deployment, and evolutionary growth of this link are vital to any long-term program, and unless a more cost-effective alternative can be determined, *Freedom's* ability to evolve must be preserved in its design.

- ADVANCED TECHNOLOGIES, in areas such as regenerative life support systems, aerobraking, cryogenic hydrogen-oxygen engines, surface nuclear power systems, in situ resource utilization, radiation protection technology, and nuclear propulsion, to name a few, are clearly necessary; today's technology simply will not suffice. Major investments must be made in developing these challenging technologies. New technologies will shape our future missions, and they may also reduce cost and lower risk.

  An advanced development/focused test program must be initiated. Independent of new ideas that may emerge, it is essential to understand the performance and capability of selected new technologies, such as aerobraking, cryogenic fluid handling in space, controlled ecological life support systems, advanced fractional-gravity spacecraft prototypes, and nuclear power systems. Experience and proof of concept in these areas are critical to proceeding with the development of the Space Exploration Initiative.

- HUMAN SUPPORT RESEARCH is the very foundation for human habitation of space, for both *Space Station Freedom* and for long-duration exploration. We need to better understand space human factors and the effects of extended-duration space flight, and to develop techniques for advanced medical care, reduced gravity countermeasures, radiation protection, and life support. In effect, we must certify human beings for journeys to Mars.

  An artificial gravity research program must be initiated in parallel with our zero-gravity countermeasure program to determine whether an artificial gravity environment must be provided for human missions to Mars. If an artificial gravity environment must be provided, the accommodation of such facilities will have a significant impact on mission configuration.

- EARTH-TO-ORBIT TRANSPORTATION represents our access to space, and the Space Shuttle is the key to current and near-term space exploration. It is the first step into space by human beings, the only way we can currently lift our astronauts into orbit. The Space Shuttle program, including the option to develop more capable Shuttle-derived launch vehicles, must be supported now and in the future, to ensure the presence of Americans in space.

Our current launch capabilities are inadequate to meet the needs of human exploration missions. The capability to transport large quantities of mass (equipment, propellant, and personnel) to low Earth orbit is essential. A heavy-lift transportation system must be pursued and targeted for operational readiness by the turn of the century. Systems being studied for this purpose include the Advanced Launch System and unmanned vehicles derived from the Shuttle system.

- **ROBOTIC MISSIONS** obtain the data that are the basis for the technological and scientific objectives of human exploration. Robotic missions also provide essential information about the environments in which human explorers and their facilities must operate, demonstrate technologies applicable to piloted missions, and serve to foster international cooperative efforts. Robotic spacecraft, clearly, will play a critical role. Robotic missions planned for the 1990s are the *Lunar Observer* and the *Mars Observer*. Candidate missions for follow-on Mars exploration are a *Mars Global Network*, and a *Mars Sample Return/Local Rover* mission.

- **SCIENCE OPPORTUNITIES** offered by the human exploration of the Moon and Mars are abundant and significant. Solar system exploration science will be advanced through the combination of robots and humans working together to push back the frontiers of knowledge. Planning for the optimum scientific utilization of the President's initiative is under way, and it will be an important ongoing element as the program develops.

The technical needs and opportunities of a human exploration program seem apparent; however, less tangible aspects — the immeasurable benefits to the Nation, the opportunity for international cooperation, and the program's effect on the education of the world's youth — are equally significant, and must be carefully considered as we begin to develop this program.

Human exploration of the Moon and Mars, technically demanding yet well within our reach, will stimulate new technologies and enhance our Nation's economic productivity. It will advance scientific knowledge and lead to discoveries about our solar system, our planet, and even life itself. It will provide entrepreneurial opportunities for commercial space enterprise. And it will help support educational programs that both challenge and inspire our youth by the adventure and the role that science and technology can play in their lives.

The civil space program of the United States has a long tradition of international cooperation in space. Such cooperation is, in fact, a hallmark of NASA programs, one that has proven advantageous to both the U.S. and its spacefaring friends. The human exploration of space lends itself to international cooperation; the scope of the activities being considered, the nature of the benefits, and the growing sophistication of space programs around the world seem to favor going to the Moon and Mars in concert with others.

Of the several approaches to human exploration examined in the last 5 years, an evolutionary strategy beginning at the Moon and going on to Mars has consistently seemed to be the most sensible. And, indeed, this is the direction the President has chosen: *Space Station Freedom* for the 1990s, back to the Moon to stay in the next century, and then on to Mars. The unfolding of this program, in concert with space science initiatives such as Mission to Planet Earth, will make the 21st Century United States civil space program second to none.

As a program plan is developed, it is necessary to keep in mind that journeys to the Moon and Mars are long-term endeavors. The President spoke of a "long-range, continuing commitment" and our commitment must be exactly that. These voyages will not occur for many years, and once begun, they will continue indefinitely. The goal has been set; the National Space Council, NASA, and others will be examining a broad range of program alternatives in order to define a strategy and implementation plan for the President and Congress to approve. With this plan, and with resources, determination, and leadership, our Nation will achieve this goal.

APPENDIX

REMARKS BY THE PRESIDENT
AT 20TH ANNIVERSARY OF
APOLLO MOON LANDING

The Steps of the Air and Space Museum
Washington, DC
July 20, 1989

"Thank you all very, very much. And thank you, Mr. Vice President, for undertaking to head the National Space Council and for demonstrating your skill for leadership there.

And thanks to all of you, who have braved the weather to join us today. Behind me stands one of the most visited places on Earth – a symbol of American courage and ingenuity. And before me stands those on whose shoulders this legacy was built – the men and women of the United States astronaut corps.

And we are very proud to be part of this unprecedented gathering of America's space veterans – and to share this stage with three of the greatest heroes of this or any other century – the crew of Apollo 11.

It's hard to believe that 20 years have passed. Neil and Buzz, who originated the moonwalk 15 years before Michael Jackson ever even thought of it.

And Michael Collins – former director of this amazing museum – and the brave pilot who flew alone on the dark side of the Moon, while Neil and Buzz touched down. Mike, you must be the only American over age 10 that night who didn't get to see the Moon landing.

And later this evening, after the crowd disperses and the Sun goes down, a nearly full Moon will rise out of the darkness and shine down on an America that is prosperous and at peace. And for those old enough to remember that historic night 20 years ago – step outside tonight with your children or your grandchildren. Lift your eyes skyward, and tell them of the flag – the American flag – that still flies proudly in the ancient lunar soil.

And for those who were not yet born, or then too young to recall – you who are the children of the new century – raise your eyes to the heavens and join us in a great dream – an American dream – a dream without end.

Project Apollo. The first men on the Moon. Some called it quixotic, impossible – never been done. But America dreamed it. And America did it. And it began on July 16th, 1969. The Sun rose a second time that morning as the awesome fireball of the Saturn 5 lifted these three pioneers beyond the clouds. A crowd of one million – including half of the United States Congress – held its breath as the Earth shook beneath their feet – and our view of the heavens was changed forevermore.

Three days and three nights they journeyed. It was a perilous, unprecedented, breathtaking voyage. And each of us remember the night.

Barbara and our daughter Dorothy were with me in our red brick house right here on the outskirts of Washington, where we moved up here to represent Houston in the United States Congress. Our 12-year-old kid, Marvin, was on a trip out West with family friends and remembers stopping at a roadside motel to watch. Second boy, Jeb, 16 that summer, teaching English and listening by radio in a small Mexican village, where electricity had yet to arrive.

The landing itself was harrowing. Alarms flashed – and a computer overload threatened to halt the mission while Eagle dangled thousands of feet above the Moon. Armstrong seized manual control to avoid a huge crater strewn with boulders. With new alarms signalling a loss of fuel – and the view now blocked by lunar dust – Mission Control began the Countdown for a mandatory abort.

America – indeed the whole world – listened – a lump in our throat and a prayer on our lips. And only 20 seconds of fuel remained. And then out of the static came the words: "Houston. Tranquility Base here. The Eagle has landed."

Within one lifetime, the human race had traveled from the dunes of Kitty Hawk to the dust of another world. Apollo is a monument to our nation's unparalleled ability to respond swiftly and successfully to a clearly stated challenge – and to America's willingness to take great risks for great rewards.

We had a challenge. We set a goal. And we achieved it.

So today is not only an occasion to thank these astronauts and their colleagues – the thousands of talented men and women across the country whose commitment, creativity, and courage brought this dream to life. It's also a time to thank the American people for their faith – because Apollo's success was made possible by the drive and daring of an entire nation committed to a dream.

In the building behind me are the testaments to Apollo and to what came before – the chariots of fire flown by Armstrong, Yeager, Lindberg and the Wrights. And in the National Archives – across the great expanse of grass – are preserved the founding documents of the idea that made it all possible – the world's greatest experiment in freedom and diversity.

And here – standing between these twin legacies – is a fitting place to look forward to the future.

Because the Apollo astronauts left more than flags and footprints on the Moon. They also left some unfinished business. For even 20 years ago, we recognized that America's ultimate goal was not simply to go there and go back – but to go there and go on.

Mike Collins said it best: "The Moon is not a destination – it's a direction."

And space is the inescapable challenge to all the advanced nations of the Earth. And there's little question that, in the 21st century, humans will again leave their home planet for voyages of discovery and exploration. What was once improbable is now inevitable.

The time has come to look beyond brief encounters. We must commit ourselves anew to a sustained program of manned exploration of the Solar System – and yes – the permanent settlement of space. We must commit ourselves to a future where Americans and citizens of all nations will live and work in space.

And today, yes, we are, the U.S. is the richest nation on Earth – with the most powerful economy in the world. And our goal is nothing less than to establish the United States as the preeminent spacefaring nation.

From the voyages of Columbus – to the Oregon Trail – to the journey to the Moon itself – history proves that we have never lost by pressing the limits of our frontiers.

Indeed, earlier this month, one news magazine reported that Apollo paid down-to-earth dividends – declaring that man's conquest of the Moon "would have been a bargain at twice the price." And they called Apollo "the best return on investment since Leonardo da Vinci bought himself a sketch pad."

In 1961, it took a crisis – the space race – to speed things up. Today we don't have a crisis. We have an opportunity.

To seize this opportunity, I'm not proposing a 10-year plan like Apollo. I'm proposing a long-range, continuing commitment.

First, for the coming decade – for the 1990s – Space Station Freedom – our critical next step in all our space endeavors.

And next – for the new century – back to the Moon. Back to the future. And this time, back to stay.

And then – a journey into tomorrow – a journey to another planet – a manned mission to Mars.

Each mission should – and will lay the groundwork for the next. And the pathway to the stars begins, as it did 20 years ago, with you – the American people. And it continues just up the street there – to the United States Congress – where the future of the Space Station – and our future as a spacefaring nation – will be decided.

And yes, we're at a crossroads. Hard decisions must be made now as we prepare to enter the next century.

As William Jennings Bryan said – just before the last turn of the century: "Destiny is not a matter of chance – it is a matter of choice. It is not a thing to be waited for – it is a thing to be achieved."

And to those who may shirk from the challenges ahead – or who doubt our chances of success – let me say this:

To this day, the only footprints on the Moon are American footprints. The only flag on the Moon is an American Flag. And the know-how that accomplished these feats is America-know-how. What Americans dream – Americans can do.

And 10 years from now – on the 30th anniversary of this extraordinary and astonishing flight – the way to honor the Apollo astronauts is not by calling them back to Washington for another round of tributes. It is to have Space Station Freedom up there, operational, and underway – a new bridge between the worlds–and an investment in the growth, prosperity and technological superiority of our nation.

And the Space Station will also serve as a stepping stone to the most important planet in the Solar System – Planet Earth.

As I said in Europe just a few days ago, environmental destruction knows no borders. A major national and international initiative is needed to seek new solutions for ozone depletion, and global warming, and acid rain. And this initiative – "Mission to Planet Earth" – is a critical part of our space program. And it reminds us of what the astronauts remember as the most stirring sight of all. It wasn't the Moon or the stars, as I remember. It was the Earth – tiny, fragile, precious, blue orb – rising above the arid desert of Tranquility Base.

The Space Station is a first and necessary step for sustained manned exploration – one that we're pleased has been endorsed by Senator Glenn and Neil Armstrong and so many of the veteran astronauts we honor today. But it's only a first step.

And today I'm asking my right hand man, our able Vice President, Dan Quayle, to lead the National Space Council in determining specifically what's needed for the next round of exploration – the necessary money, manpower, and material – the feasibility of international cooperation – and develop realistic timetables, milestones along the way. The Space Council will report back to me as soon as possible with concrete recommendations to chart a new and continuing course to the Moon and Mars and beyond.

There are many reasons to explore the universe, but 10 very special reasons why America must never stop seeking distant frontiers – the 10 courageous astronauts who made the ultimate sacrifice to further the cause of space exploration. They have taken their place in the heavens, so that America can take its place in the stars.

Like them, and like Columbus, we dream of distant shores we've not yet seen.

Why the Moon? Why Mars? Because it is humanity's destiny to strive, to seek, to find. And because it is America's destiny to lead.

Six years ago, Pioneer 10 sailed beyond the orbits of Neptune and of Pluto – the first man-made object to leave the Solar System. Its destination unknown. It's now journeyed through the tenures of five Presidents – four billion miles from Earth.

In the decades ahead, we will follow the path of the Pioneer 10. We will travel to neighboring stars, to new worlds, to discover the unknown. And it will not happen in my lifetime, and probably not during the lives of my children, but a dream to be realized by future generations must begin with this generation. We cannot take the next giant leap for mankind tomorrow unless we take a single step today.

To all of you here, our able director of NASA and others who've served so well – to all of you here – and especially the astronauts – we wish you good luck in your quests, wherever that may take you. Godspeed to you, one and all. And God bless the United States of America.

Thank you all very, very much."